# Superstring Phenomenology

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# Outline

- Motivation
- Superstrings
- String Compactifications
    - Model building
    - Moduli stabilization and supersymmetry breaking
    - The string landscape and the swampland
- String Cosmology
    - Before Inflation?
    - Models of String Inflation
    - Post-inflation
    - Alternatives

# Recommended reading

- L. Ibanez, A. Uranga; String theory and particle physics, CUP (2009).
- A. Hebecker, Lectures on Naturalness, String Landscape and Multiverse, arXiv/2008.10625.
- Agmon, Bedroya, Kang, Vafa; Lectures on the string landscape and the swampland, arXiv/2212.06187.
- M. Cicoli, J. Conlon, A. Maharana, S. Parameswaran, F. Quevedo, I. Zavala; String Cosmology: from the early universe to today, arXiv/2303.04819.

# Motivation

*Our purpose in theoretical physics is not to describe the world as we find it, but to explain-in terms of a few fundamental principles- why the world is the way it is.*

*Steven Weinberg*

# Fundamental Theories:

## Special Relativity and Quantum Mechanics

# Poincaré Group

Wigner 1939

**Massive particles:** (Little group SO(3)) $p = (m, 0, 0, 0)$

$$|m, J; p_\mu, s\rangle \text{ with } s = -J, -J+1, \cdots, J \text{ and } p^2 = m^2$$

**Tachyons?**

**Massless particles:** (Little group E2) $p = (E, 0, 0, E)$

→ ∞-dimensional representations (CSR): not observed ??

Restricted Little group: O(2) in E2: $|p_\mu, \lambda\rangle$ with $\lambda = 0, \pm 1/2, \pm 1, \cdots$.

Theories for spins 0,1/2,1: **Quantum Field Theories (QFT)**

Massless spins 3/2,2: (super) gravity: **Effective Field Theories (EFT)**

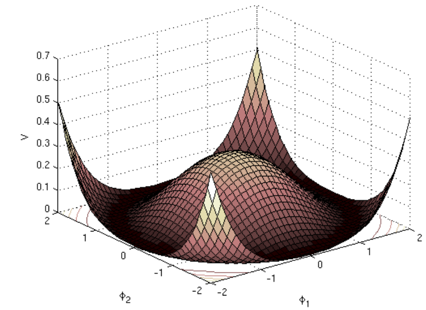
# “General Predictions” of QFT

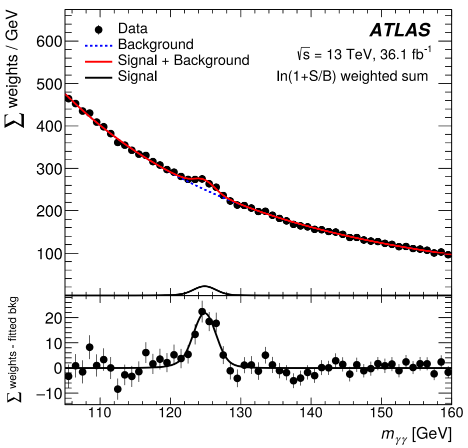
- **Identical particles**
- **Antiparticles**
- **CPT**
- **Spin-statistics**
- **‘Decoupling’ (physics organised by scales, EFTs)**

# Standard Model 1

- **Particle physics**

| Name | Label | $\mathrm{SU}(3)_C,\ \mathrm{SU}(2)_L,\ \mathrm{U}(1)_Y$ | Spin |
|---|---|---|---|
| Quarks | $Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$ | $(\mathbf{3}, \mathbf{2}, +\frac{1}{6})$ | $\frac{1}{2}$ |
| | $u_R^i$ | $(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3})$ | $\frac{1}{2}$ |
| | $d_R^i$ | $(\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{3})$ | $\frac{1}{2}$ |
| Leptons | $L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$ | $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ | $\frac{1}{2}$ |
| | $e_R^i$ | $(\mathbf{1}, \mathbf{1}, -1)$ | $\frac{1}{2}$ |
| | $\nu_R^{i*}$ | $(\mathbf{1}, \mathbf{1}, 0)$ | $\frac{1}{2}$ |
| Higgs | $H$ | $(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$ | 0 |
| Gluons | $g_\alpha$ | $(\mathbf{8}, \mathbf{1}, 0)$ | 1 |
| $W/Z$-Bosons | $W^\pm, Z^0$ | $(\mathbf{1}, \mathbf{3}, 0)$ | 1 |
| Photon | $\gamma$ | $(\mathbf{1}, \mathbf{1}, 0)$ | 1 |
| Graviton* | $h_{\mu\nu}$ | $(\mathbf{1}, \mathbf{1}, 0)$ | 2 |

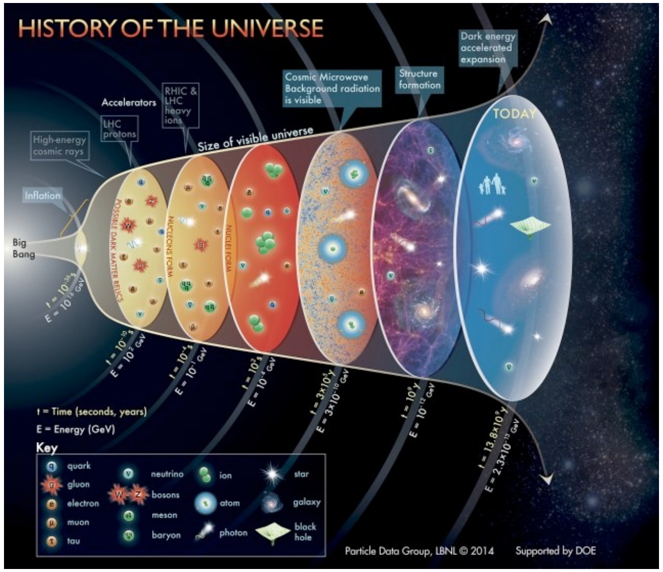


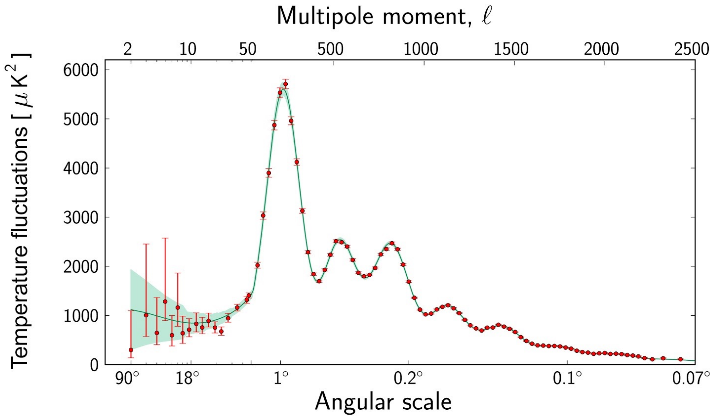



Triumph of gauge field theories and effective field theories (EFT) !

# Standard Model 2

- **Cosmology**




$\Lambda$CDM + inflation

(source of almost scale invariant, gaussian, adiabatic density perturbations)

Note: There is no theory behind (origin of dark matter, dark energy, inflation, etc.)

# Compelling Structure of the SM

- Gauge theories unique
- Higgs mechanism
- One spin/helicity s= 2 graviton
- No interacting higher spin s>2 massless states
- Choice of gauge groups, representations, couplings

*Missing spin 3/2 requires supersymmetry!

# SM+Gravity as EFT

**EFT: scalar field**

$$\mathcal{L} = \underbrace{\underbrace{\partial^\mu\phi\partial_\mu\phi - m^2\phi^2 - g\phi^3 - \lambda\phi^4}_{\text{Renormalisable}} + \frac{\alpha}{\Lambda}\phi^5 + \frac{\beta}{\Lambda^2}\phi^6 + \cdots}_{\text{Non-Renormalisable}}$$

**EFT: Einstein gravity**

$$\mathcal{L}_{EH} = M_P^2\, R^{(4)}\sqrt{-g}$$

$$\mu \ll M_P = \sqrt{\frac{\hbar c}{G_N}} \sim 10^{19}\mathrm{GeV}\,.$$

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_P}h_{\mu\nu} \quad \Rightarrow \quad M_P^2 R^{(4)} = (\partial h)^2 + \frac{h}{M_P}(\partial h)^2 + \frac{h^2}{M_P^2}(\partial h)^2 + \ldots\,.$$

**EFT: SMEFT**

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{M}\mathcal{L}_5 + \frac{1}{M^2}\mathcal{L}_6 + \mathcal{O}\left(\frac{1}{M^3}\right)\,.$$

$$\mathcal{L}_{SM} = \mathcal{L}^{\text{gauge}} + \mathcal{L}_F^{\text{kinetic}} + \mathcal{L}_F^{\text{Yukawa}} + \mathcal{L}^{\text{Higgs}}$$

**EFT: SM + gravity**

$$\mathcal{L}_{SM} \to \sqrt{-g}\left(\mathcal{L}'_{SM} + \Lambda + M_P^2 R + \ldots\right)$$

$$\mathcal{L}'_{SM} = \mathcal{L}_{SM}[D_\mu \to \mathcal{D}_\mu]$$

**BUT …**

# Open Questions

- Why? (3+1 (dimensions, families, interactions);
  + some 20 parameters (masses, couplings))

- Naturalness (hierarchy, cc, strong CP)

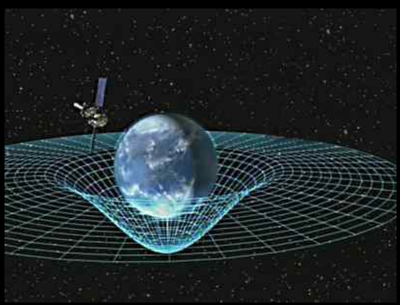
- ‘Technical’ (confinement,...)

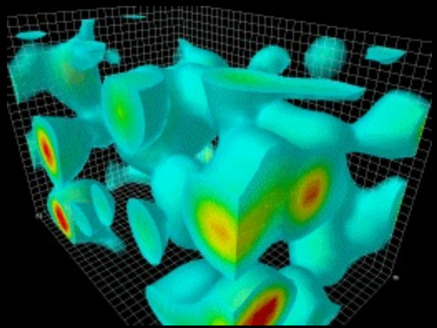
- Cosmology (dark matter, baryogenesis, density perturbations of CMB, origin/alternatives to inflation,..., big-bang)

- UV completion of gravity

# FUNDAMENTAL PROBLEM

## Quantum Gravity

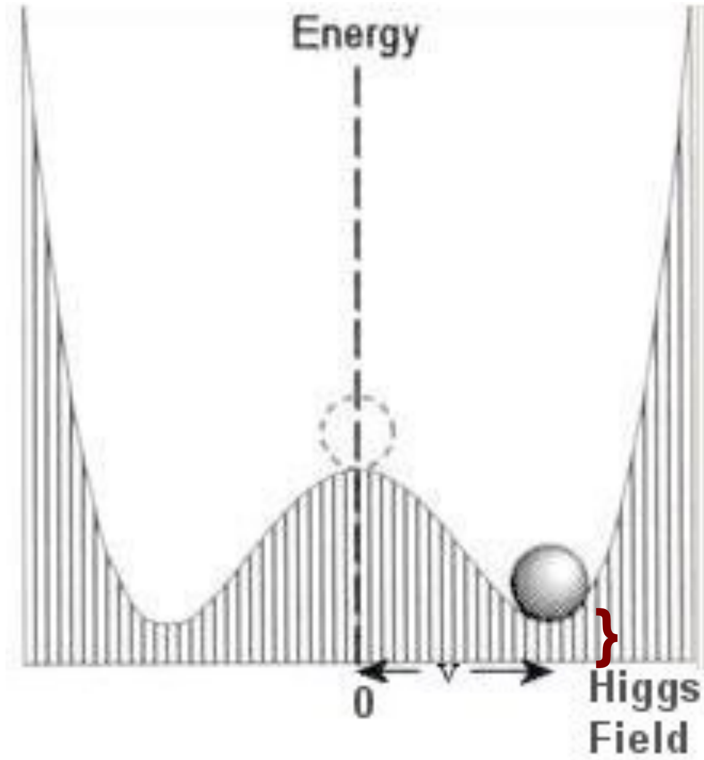




Planck scale: $M_{Planck} = \sqrt{hc/G} \approx 10^{19}$ GeV

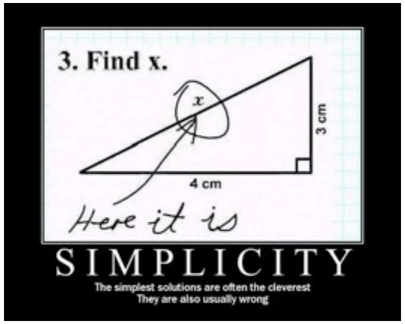
$L_{Planck} = \sqrt{hG/c^3} \approx 10^{-33}$ cm

# Greatest puzzle: Cosmological constant



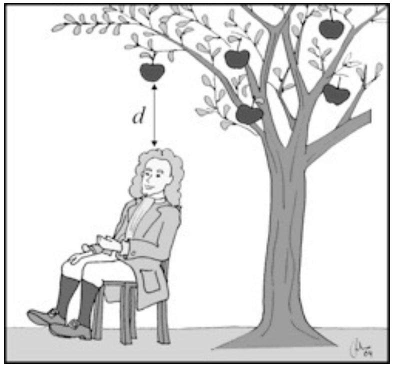

**Cosmological constant =**
**0.0000000000000000000000000000000000000000000000000000000000000000**
**0000000000000000000000000000000000000000000000000000001 $M_{Planck}^4$**
**????**

# Approaches to BSM




Simplicity

Follow your nose

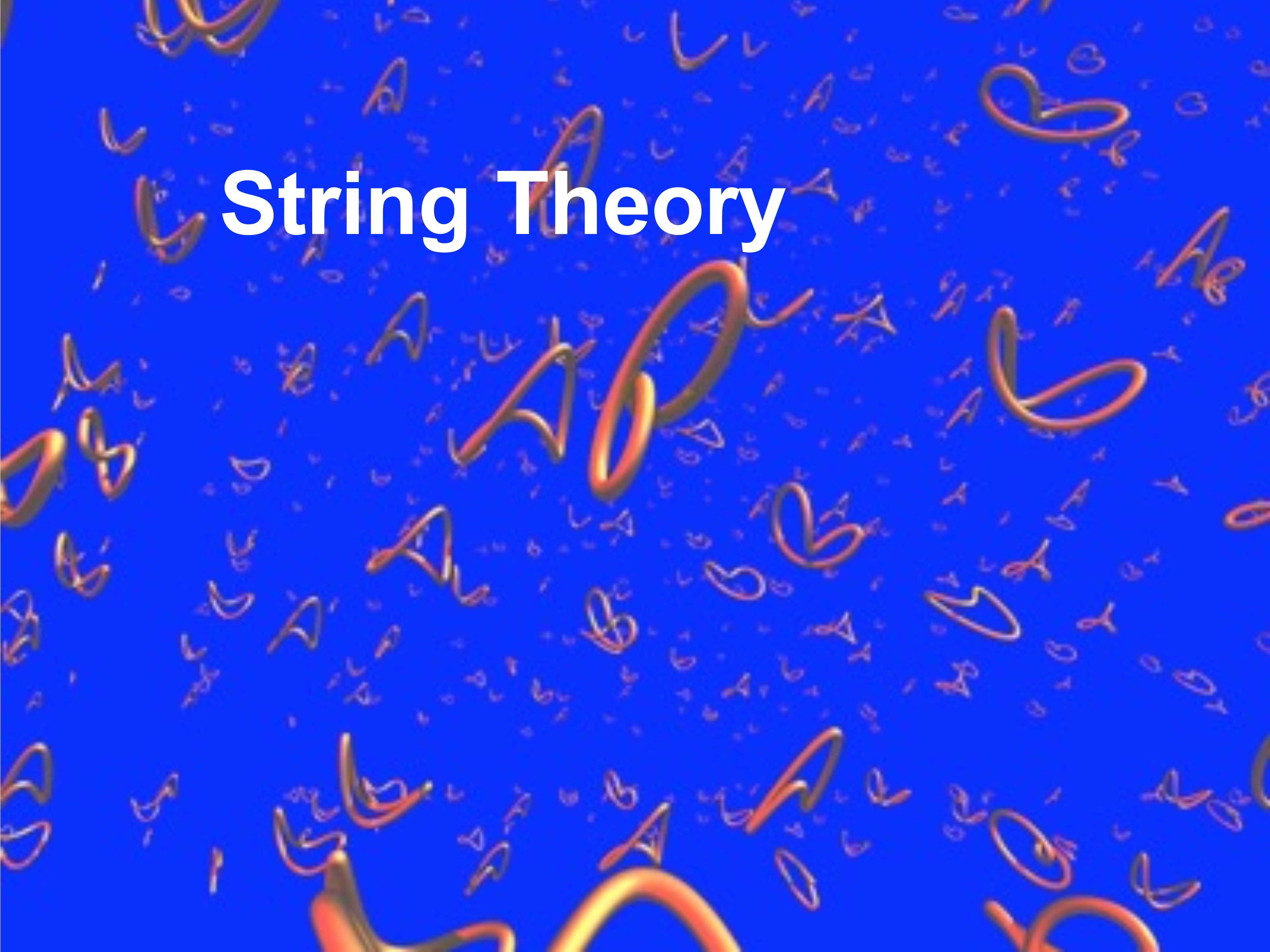



Top-down

Bottom-up

# Superstrings

# String Theory

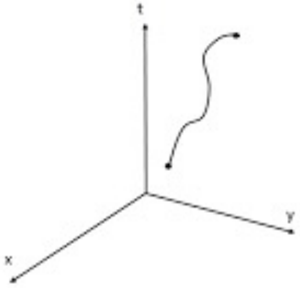


# String Theory in a Nutshell

**Relativistic point particle mass m**

$$S = -m \int_{\gamma} \mathrm{d}s,$$

$$ds = \sqrt{\eta_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}}\, d\tau$$



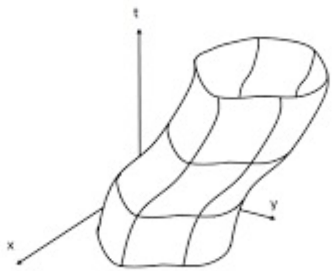

$$\frac{d}{d\tau}\left(m \frac{dx^\mu}{d\tau}\right) = m\ddot{x}^\mu = 0$$

**Free particle**

$$S = -m \int \sqrt{-\dot{x}^2} d\tau - q \int A_\mu dx^\mu \,.$$

**Electromagnetic interaction**

## Relativistic string of tension T




**Nambu-Gotto action**

$$S_{\rm NG}[X] = -TA(\Sigma) = -T\int_\Sigma d^2A = -\frac{1}{2\pi\alpha'}\int d\sigma d\tau \sqrt{\left(\dot X\cdot X'\right)^2 - \left(\dot X\right)^2\left(X'\right)^2}$$

$$\alpha' \equiv \frac{1}{2\pi T}\,.$$

**String analogue of E&M coupling?**

$$Q\int B_{\mu\nu}dX^\mu dX^\nu$$

## Polyakov action

$$S_{\rm P}[X,h] = -\frac{T}{2}\int d^2\sigma\sqrt{h}h^{\alpha\beta}\partial_\alpha X^\mu\partial_\beta X^\nu\eta_{\mu\nu}$$

$$h_{\alpha\beta}(\sigma)\to e^{2\Lambda(\sigma)}h_{\alpha\beta}(\sigma)$$

**Weyl (conformal) invariance**
**together with Lorentz and 2d reparametrisations**

**Equation of motion for X:**

$$\frac{1}{\sqrt{h}}\partial_\alpha\left(\sqrt{h}h^{\alpha\beta}\partial_\beta X^\mu\right) = 0$$

**Equation of motion for h gives the Nambu-Gotto action**

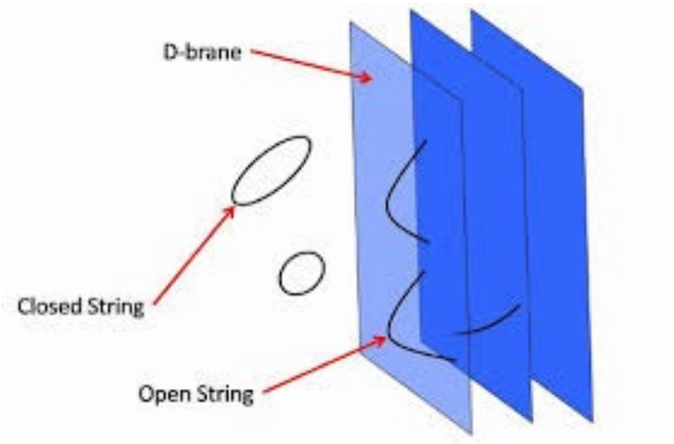
# Boundary conditions

**Closed Strings** periodic

**Open Strings** $$\delta S = \frac{1}{2\pi\alpha'}\int d^2\sigma\,(\partial^2 X)\cdot\delta X - \frac{1}{2\pi\alpha'}\int d\tau\,(\partial_\sigma X^\mu)\cdot\delta X_\mu\Big|_{\sigma=0}^{\sigma=\pi}$$

$\partial_\sigma X^\mu = 0$ **Neuman**

$\delta X_\mu = 0$ **Dirichlet**




Neuman in time and p-spatial dimensions

Dirichlet in D-p dimensions: **D-branes**

$$\int B_{M_1 \dots M_{p+1}}\, \mathrm{d}x^{M_1} \wedge \dots \wedge \mathrm{d}x^{M_{p+1}}$$

**p+1 rank antisymmetric tensor couples to a p-dimensional brane**

# Critical Dimensions

**Conformal gauge** $h_{\alpha\beta} = \eta_{\alpha\beta}$

**Conformal (trace) anomaly:** $T_{z\bar{z}} = -\frac{c}{24}\mathcal{R}.$ **c=0.**

**Each scalar field $X_\mu$ contributes c=1.**

**Ghost system contributes c=-26**

**c=D-26**

$$D = 26.$$ Bosonic strings

**Add supersymmetry: 2-dimensional fermions c=1/2 each, ghosts c=-15 Then:**

$$D = 10$$ Supersymmetric strings

# Spectrum

**Solution to wave equation** $\partial^\mu \partial_\mu X^M = 0$

$$X^M(\sigma,\tau) = X_R^M(\tau-\sigma) + X_L^M(\tau+\sigma)$$

**Mode expansion**

$$X_R^M(\tau-\sigma) = x_R^M + p_R^M(\tau-\sigma) + \frac{i}{2}\sum_{n\neq 0}\frac{1}{n}\alpha_n^M\, e^{-2in(\tau-\sigma)}$$

$$X_L^M(\tau+\sigma) = x_L^M + p_L^M(\tau+\sigma) + \frac{i}{2}\sum_{n\neq 0}\frac{1}{n}\tilde{\alpha}_n^M\, e^{-2in(\tau+\sigma)}$$

**Hamiltonian (mass formula)** $M^2 = N_R + N_L - 2.$ **Level matching** $N_L = N_R$

**Vacuum (tachyon)** $|0\rangle$

**Massless states (closed string)** $\alpha_{-1}^M \tilde{\alpha}_{-1}^N |0\rangle$ $G_{MN},\, B_{MN},\, \Phi$

**Open strings:**

$|0\rangle$ Tachyon

$\tilde{\alpha}_{-1}^N |0\rangle$ Massless U(1) gauge field

***In superstrings: tachyons projected out also no CSRs!**

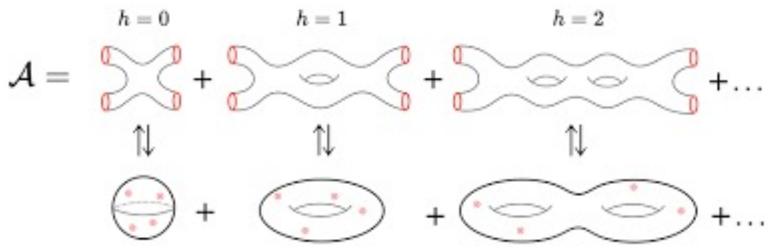
# Two EFTs

**2-dimensional**

$$S = \frac{1}{\alpha'} \int d\sigma d\tau \left\{ \left(G_{MN}(X) + B_{MN}(X)\right) \partial^\mu X^M \, \partial_\mu X^N + \alpha' \Phi(X) \, {}^{(2)}R \right\}.$$

**Interactions**

$$\langle \text{out} | \, \text{evolution} \, | \text{in} \rangle \; = \sum_{\text{worldsheets}} \int [\mathcal{D}X] \, e^{-S_{\text{P}}[X]} \, \mathcal{O}_{\text{in}}[X] \, \mathcal{O}_{\text{out}}[X]$$




**Each UV finite!**

**26/10-dimensional**

$$S = \int d^D X \sqrt{G} e^{-\Phi} \left\{ R - \frac{1}{12} \nabla_M B_{NP} \nabla^M B^{NP} + \nabla_M \Phi \nabla^M \Phi - \frac{D - 26}{3} \right\}$$

**String theory predicts Einstein's gravity plus…!!!**

**Dilaton Φ loop counting parameter or string coupling**

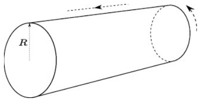
# Low energy states in Superstring/M theories

| Theory | Dimension | Supercharges | Massless Bosons |
|---|---|---|---|
| Heterotic $E_8 \times E_8$ | 10 | 16 | $g_{MN}, B_{MN}, \phi$ $A_M^{ij}$ |
| Heterotic $SO(32)$ | 10 | 16 | $g_{MN}, B_{MN}, \phi$ $A_M^{ij}$ |
| Type I $SO(32)$ | 10 | 16 | $g_{MN}, \phi, A_M^{ij}$ $C_{MN}$ |
| Type IIA | 10 | 32 | $g_{MN}, B_{MN}, \phi$ $C_M, C_{MNP}$ |
| Type IIB | 10 | 32 | $g_{MN}, B_{MN}, \phi$ $C_0, C_{MN}, C_{MNPQ}$ |
| M-Theory | 11 | 32 | $g_{MN}, C_{MNP}$ |

# String Compactifications

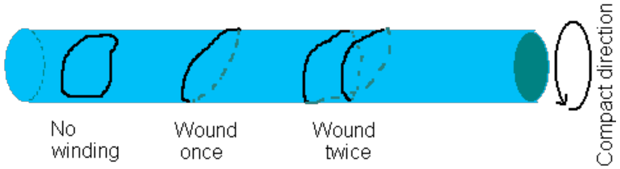
# Simple Compactifications

**$X^9$: $S^1$ Circle of radius R** $X^9$=$X^9$+ $2\pi$ R

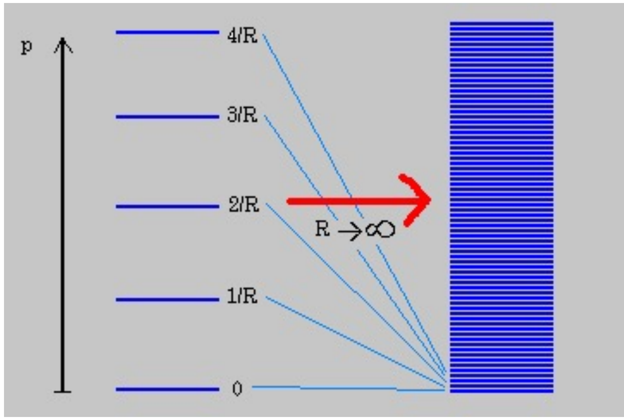



$$p_R = m/2R - nR \qquad\qquad p_L = m/2R + nR$$

m,n integers: momentum and winding!

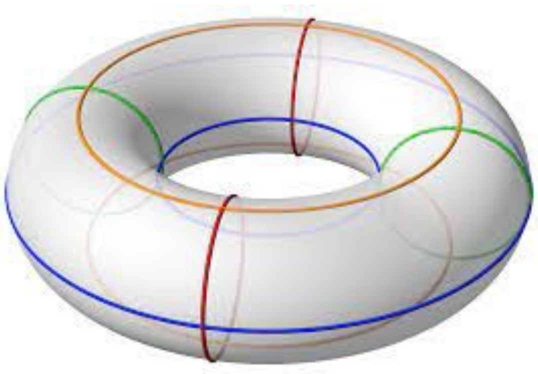



$$M^2 = N_R + N_L - 2 + \frac{m^2}{4R^2} + n^2R^2, \qquad N_R - N_L = mn.$$



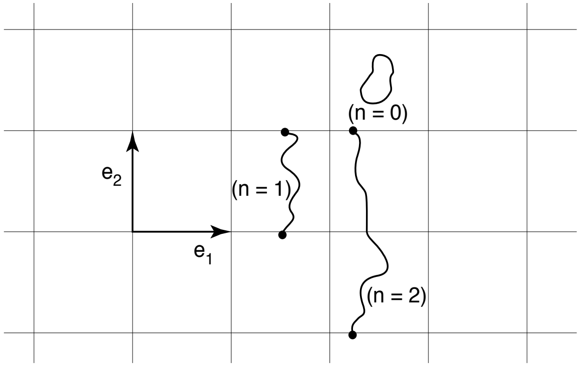

- **n=0, infinite tower of massive (Kaluza Klein) states mass=m/R**
- **Massless n=m=0: vector fields $U(1)_L \otimes U(1)_R$**
- **$n\neq 0$ winding states mass proportional to R**
- **m=n=$\pm$1 $N_R$=1, $N_L$=0 or $N_R$=0, $N_L$=1 enhanced symmetry $SU(2)_L \otimes SU(2)_R$ at $R^2$=1/2**
- **R is arbitrary: a modulus!**
- **Duality !** $R \leftrightarrow \frac{1}{2R} \qquad m \leftrightarrow n.$ **$R^2$=1/2 self-dual**

# Toroidal Compactification



$$\begin{matrix} & h^{1,1} & \\ h^{1,0} & & h^{0,1} \\ & h^{0,0} & \end{matrix} = \begin{matrix} & 1 & \\ 1 & & 1 \\ & 1 & \end{matrix}$$

Hodge diamond




$$U \equiv \frac{G_{12}}{G_{22}} + i\,\frac{\sqrt{G}}{G_{22}}$$ Complex structure

$$T \equiv B_{12} + i\,\sqrt{G}.$$ Kahler structure

$$p_L^2 = \frac{1}{2U_2T_2}\|(n_1 - n_2\,U) - T\,(m_2 + m_1\,U)\|^2$$

$$p_R^2 = \frac{1}{2U_2T_2}\|(n_1 - n_2\,U) - T^*(m_2 + m_1\,U)\|^2$$

$$U \to \frac{a\,U + b}{c\,U + d} \qquad T \to \frac{a\,T + b}{c\,T + d} \qquad T \leftrightarrow U. \qquad ad - bc = 1$$

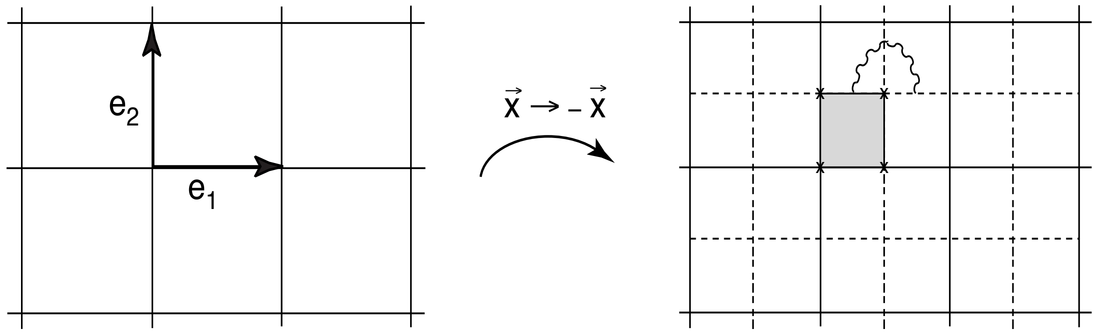
Modular invariance    T-duality    Mirror symmetry

$$SL(2,\mathbf{Z})_U \otimes SL(2,\mathbf{Z})_T = O(2,2,\mathbf{Z})$$

**Moduli space** $SL(2,\mathbb{R})/O(2) \otimes SL(2,\mathbb{R})/O(2) \;\cong\; O(2,2,\mathbb{R})/(O(2) \otimes O(2))$

**In general** $\mathcal{M} = O(d,d,\mathbb{R})/O(d) \otimes O(d)$    **T-Duality** $O(d,d,\mathbf{Z})$

# Orbifolds




$O^2 \equiv T^2/\mathbf{Z}_2$

**In general** $O^d \equiv T^d/\mathcal{P} \equiv \mathbb{R}^d/\mathcal{S}.$

$\{(0,0),(0,1/2),(1/2,0),(1/2,1/2)\}$ **Fixed points**

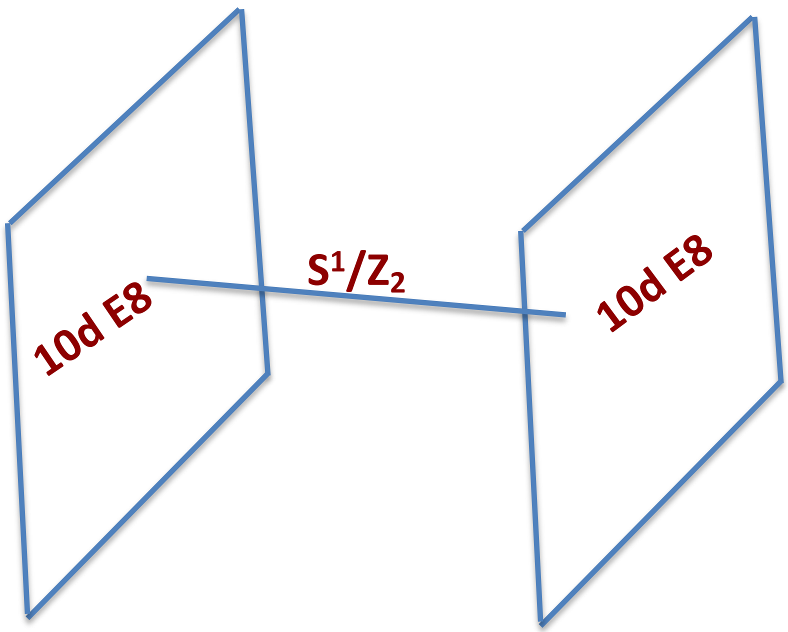
**Strings on orbifolds**

- **Chiral N=1 SUSY**
- **Still essentially flat except for fixed points**
- **Extra sectors: twisted sectors**

**Quasi realistic models e.g. $T^6/Z_3$ heterotic: 3 families SU(3)xSU(2)xU(1)x…**

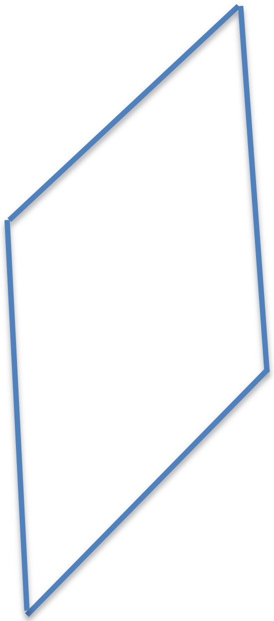
# Horava Witten

**11d on $S^1/Z_2$ (interval) gives 10d heterotic $E_8 x E_8$ (strong coupling)**



# Orientifold Planes

Combine orbifold in target space with orbifold in string worldsheet (orientation)
Fixed planes with positive or negative tension.



O-planes

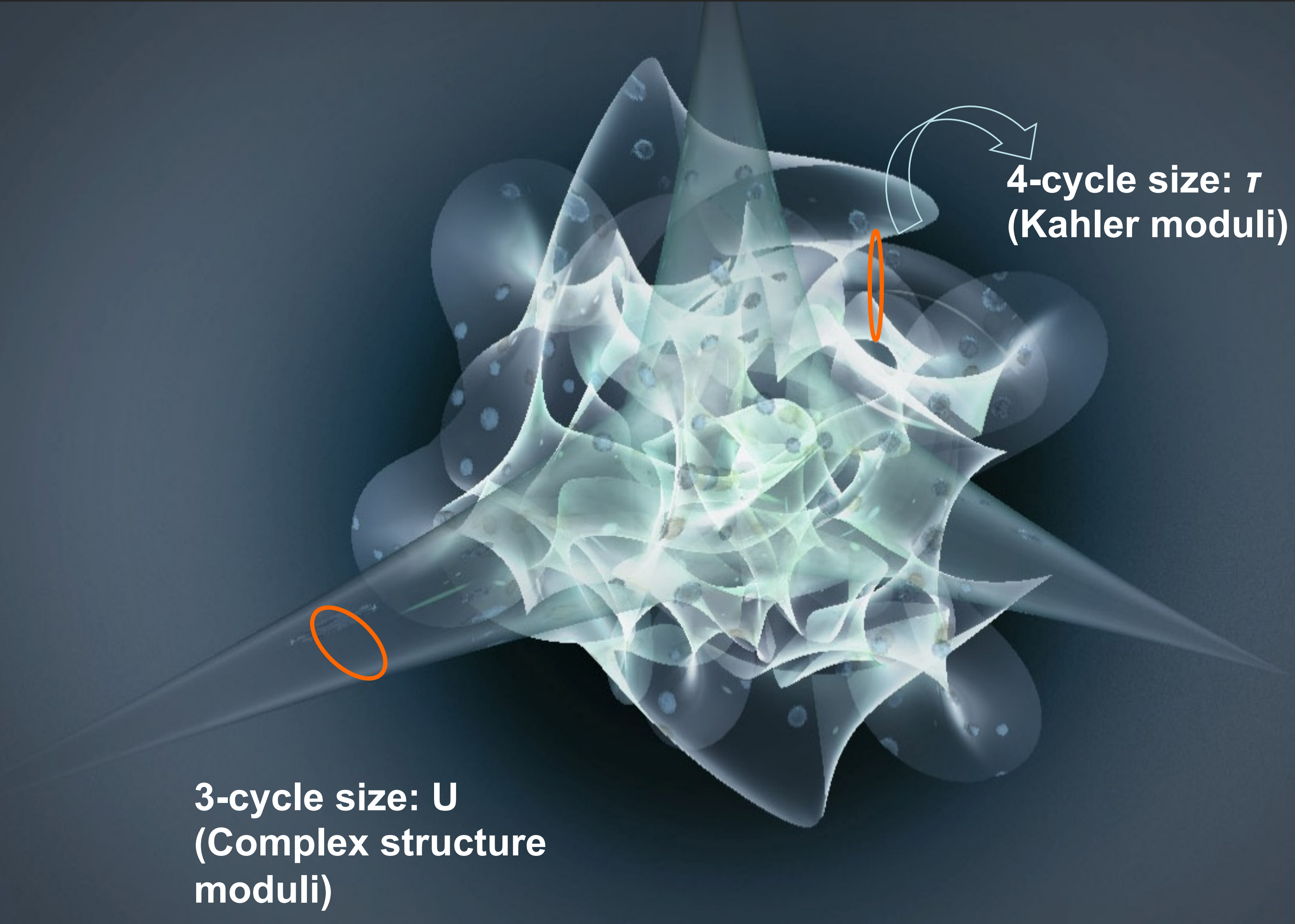
O-planes in IIA or IIB string theory break half supersymmetry

# Calabi Yau Manifolds/Orientifolds

- 3d Complex Kahler manifolds with SU(3) holonomy (vanishing first Chern class)
- 1d CY torus T2, 2d CY K3 surface, 3d and higher many
- Admit Ricci flat metric but not known explicitly
- Heterotic/type I on CY give 4D Minkowski N=1 theory
- Type II on CY orientifold also 4d Minkowski N=1 SUSY
- Hodge diamond

$$
\begin{array}{ccccccc}
 & & & h^{3,3} & & & \\
 & & h^{3,2} & & h^{2,3} & & \\
 & h^{3,1} & & h^{1,1} & & h^{1,3} & \\
h^{3,0} & & h^{2,1} & & h^{1,2} & & h^{0,3} \\
 & h^{2,0} & & h^{2,2} & & h^{0,2} & \\
 & & h^{1,0} & & h^{0,1} & & \\
 & & & h^{0,0} & & &
\end{array}
\;=\;
\begin{array}{ccccccc}
 & & & 1 & & & \\
 & & 0 & & 0 & & \\
 & 0 & & h^{1,1} & & 0 & \\
1 & & h^{2,1} & & h^{2,1} & & 1 \\
 & 0 & & h^{1,1} & & 0 & \\
 & & 0 & & 0 & & \\
 & & & 1 & & &
\end{array}
$$

# Calabi Yau


4-cycle size: $\tau$
(Kahler moduli)
3-cycle size: U
(Complex structure
moduli)

# Examples of Calabi-Yau

- Blow-up toroidal orbifolds

- Surfaces in Projective spaces (algebraic geometry) **e.g.** $P \equiv z_1^{12} + z_2^{12} + z_3^6 + z_4^6 + z_5^2 = 0$

  $\mathbb{P}^4_{(k_0,k_1,k_2,k_3,k_4)} \quad (1,1,2,2,6)$

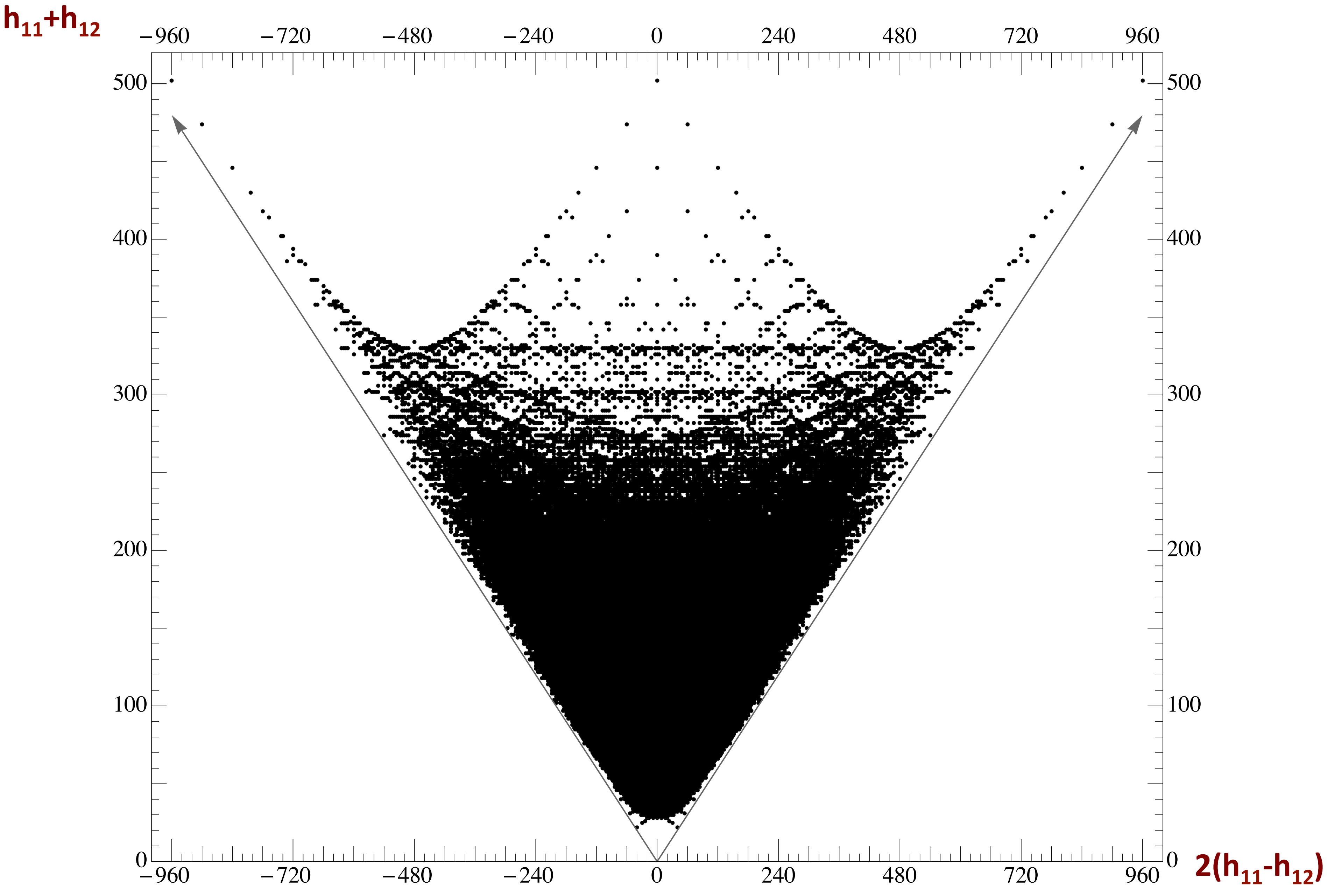
- Hypersurfaces in Toric varieties, etc.

**Database and tools:**

http://hep.itp.tuwien.ac.at/~kreuzer/CY/

https://cy.tools/

# Mirror Symmetry



# Realistic Model Building

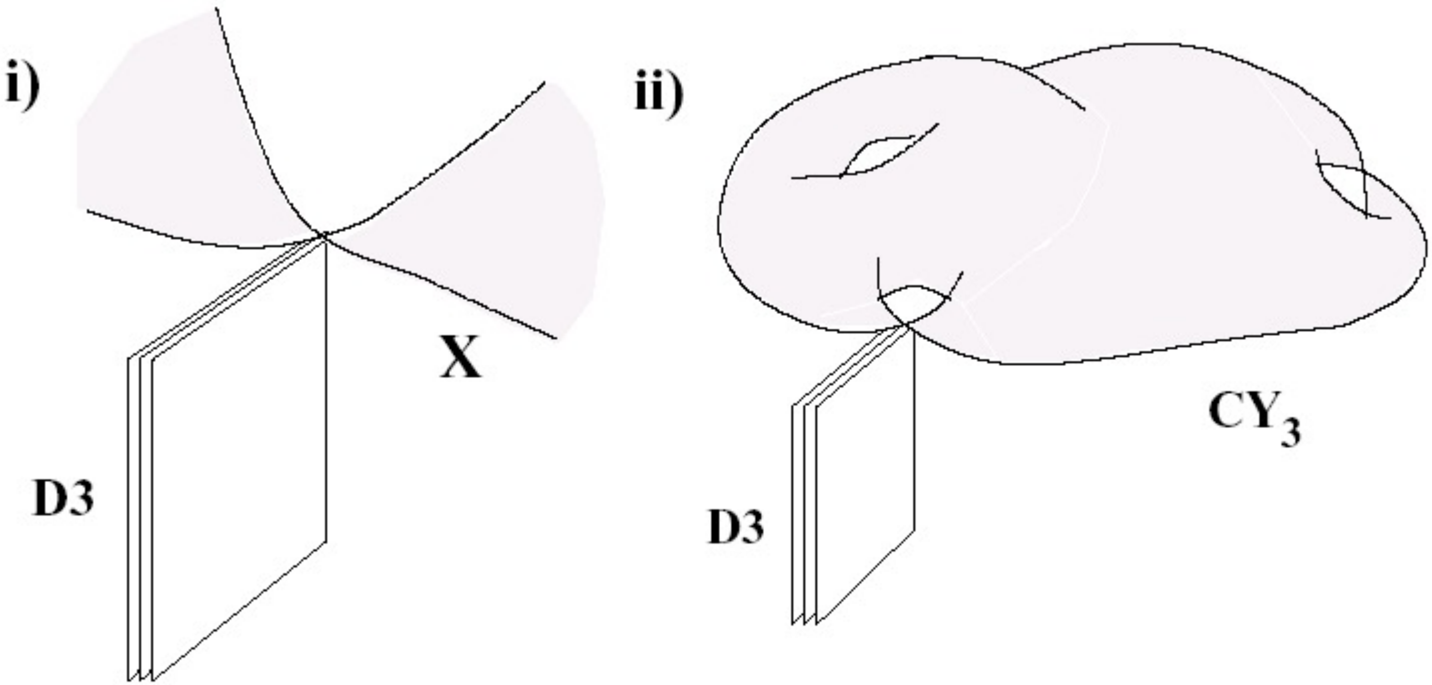
# Challenges for String Models

- Gauge and matter structure of SM
- Hierarchy of scales + masses (including neutrinos)
- Flavor CKM, PMNS mixing, CP no FCNC
- Hierarchy of gauge couplings (unification?)
- 'Stable' proton + baryogenesis
- Inflation or alternative for CMB fluctuations
- Dark matter (+ avoid overclosing)
- Dark radiation ($N_{eff}$~3.04)
- Dark energy

**N.B. If ONE of them does not work, rule out the model!!!**

# String Model Building:

- Global Models (e.g. Heterotic)
- Local Brane Models (e.g. IIB, F-theory)



# Calabi-Yau Spaces and Brane World

# New tools: Machine Learning

- **Machine (supervised and reinforcement) learning**

Lukas et al 2018-2019

- **Genetic algorithms**

Abel et al et al 2021

1. **For model selection**

2. **Computing explicit metrics of Calabi-Yau manifolds**

Anderson et al, Douglas et al, Jejjala et al 2020

Review Ruehle Phys Rep. 2020

# Recent Progress

- **N =$10^{15}$ F-theory models with MSSM spectrum** Cvetic et al 2019
- **N>$10^{23}$ heterotic models with MSSM spectrum** Constantin et al 2019

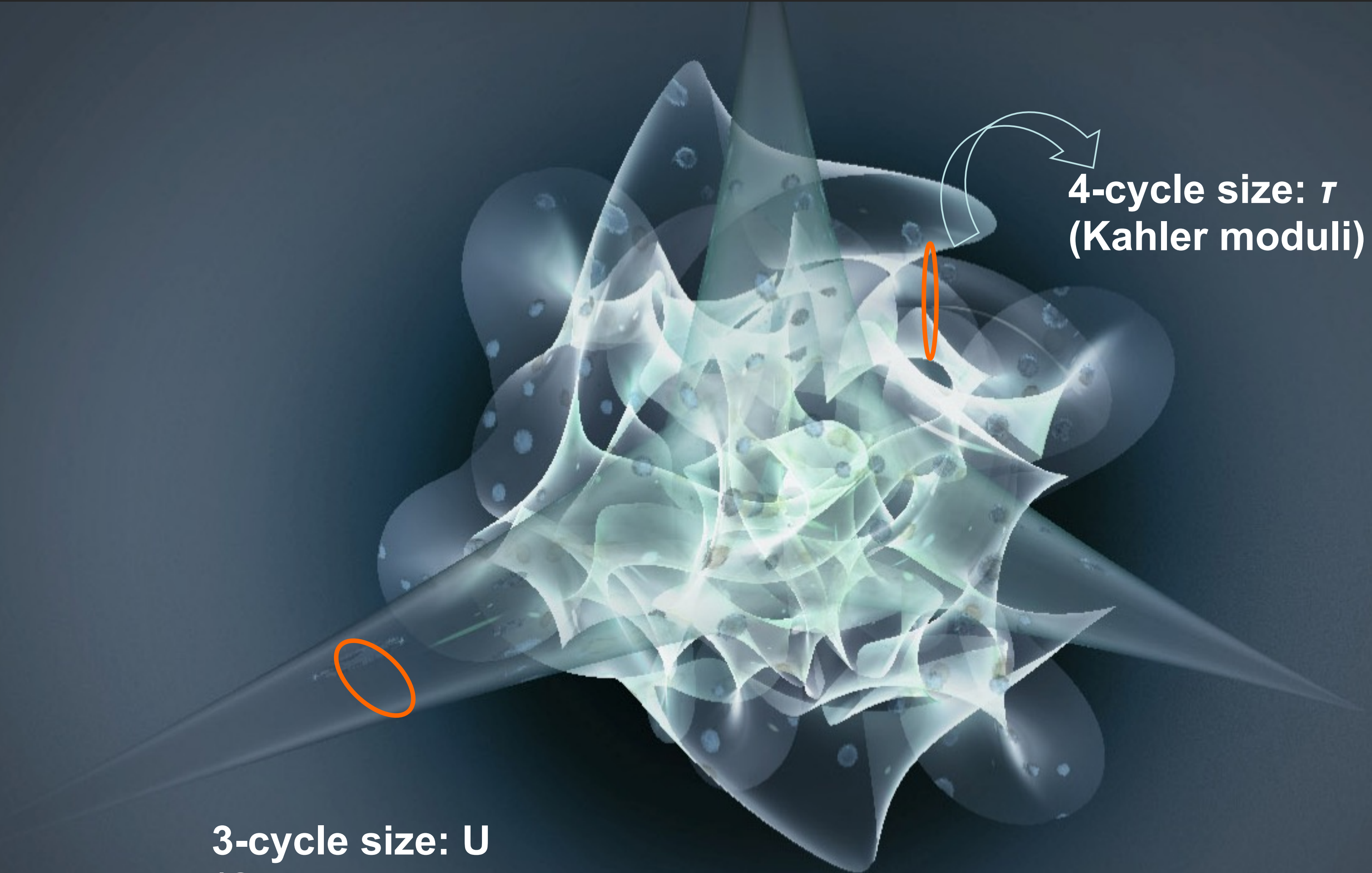
**BUT**

**Big problem: moduli stabilization**

**(hundreds of massless gravitationally coupled scalar fields, 5th force constraints rules them out)**

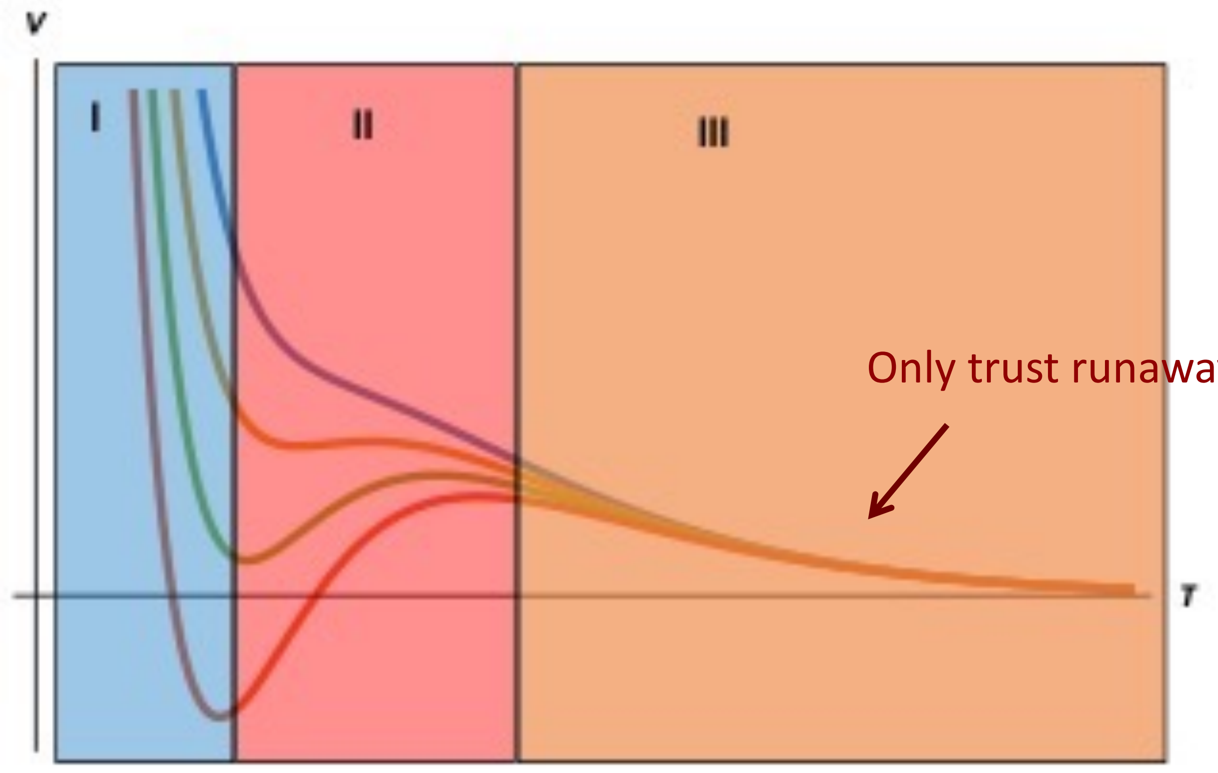
# Moduli Stabilisation and Supersymmetry Breaking

# MODULI STABILISATION



# Dine-Seiberg Problem

Dine, Seiberg 1985




Only trust runaway part

$\mathbf{V} \longrightarrow \mathbf{0}$ at weak coupling and large volume, then minimum may be at strong coupling/small volume beyond control of string perturbation theory

# Approaches to DS Problem

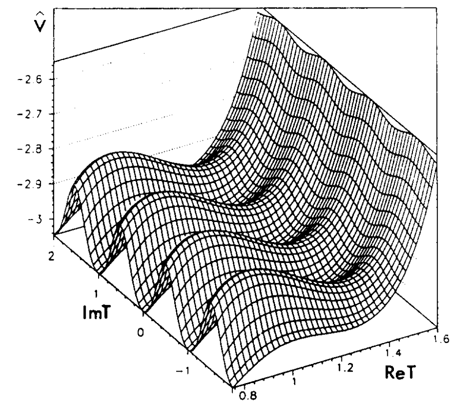
- 1980s Racetrack models

$$W = Ae^{-\frac{2\pi S}{N}} + Be^{-\frac{2\pi S}{M}}$$

$$S = \frac{NM}{M-N}\log\left(-\frac{MB}{NA}\right)$$

Krasnikov 1987

- 1990s T or S Duality



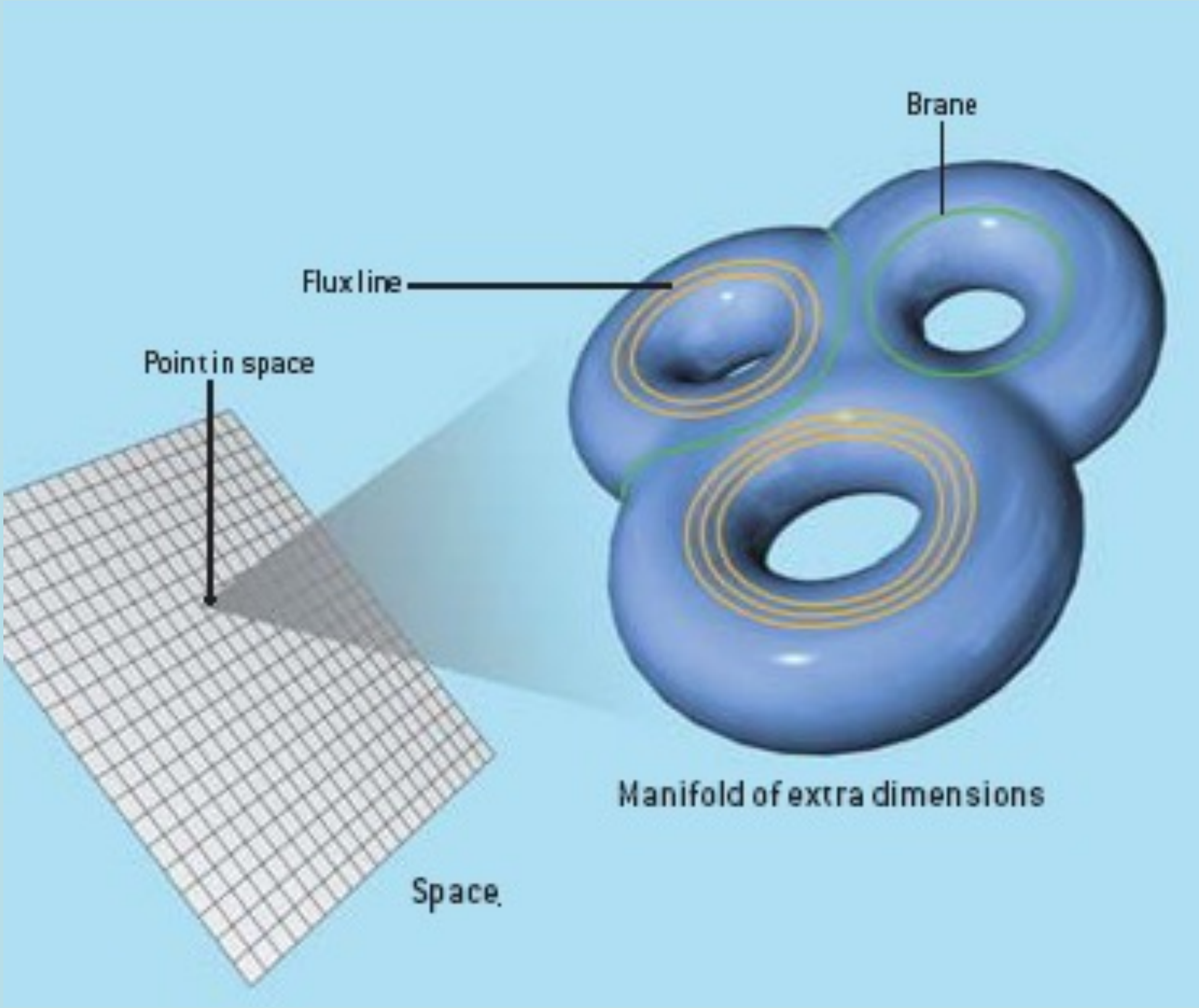

$$W(S,T) \sim \eta(iT)^{-6}\exp(-3S/8\pi b)$$

Font et al, Ferrara et al 1990

- 2000s Flux compactifications

Sethi et al., Giddings et al 2002…

# Flux compactifications



# 4D Moduli

**10D massless spectrum:**

- NSNS sector: $g_{MN}, B_2\,(dB_2 = H_3),\ \varphi\,(e^{<\varphi>} = g_s)$
- RR sector: $C_0, C_2\,(dC_2 = F_3),\ C_4$

**4D moduli:**

- Axio-dilaton: $S = e^{-\varphi} + i\,C_0$
- Complex structure moduli: $U_\alpha \quad \alpha = 1,\ldots,h^-_{1,2}$
- Kahler moduli:

$$T_i = \tau_i + i\,b_i^+, \quad \tau_i = \mathrm{Vol}(D_i), \quad b_i^+ = \int_{D_i} C_4, \quad i = 1, \ldots, h^+_{1,1},$$

$$G_j = c_j - iSb_j^-, \quad c_j = \int_{\hat{D}_j} C_2, \quad b_j^- = \int_{\hat{D}_j} B_2, \quad j = 1, \ldots, h^-_{1,1}$$

# Fluxes in IIB Compactifications

- **Tree-level Kahler potential:**

$$K_{tree} = -2\ln \mathcal{V}(T_i + \bar{T}_i) - \ln(S + \bar{S}) - \ln\left( i \int_{CY} \Omega(U) \wedge \bar{\Omega} \right)$$

- **Tree-level superpotential:**

$$W_{tree} = \int_{CY} G_3 \wedge \Omega(U) \qquad G_3 = F_3 + iSH_3$$

- **Flux quantisation:**

$$\frac{1}{2\pi\alpha'} \int_{\Sigma_3^k} H_3 = n_k \qquad \frac{1}{2\pi\alpha'} \int_{\Sigma_3^k} F_3 = m_k \qquad \mathrm{k} = 1,\ldots,n = 2h^{1,2} + 2$$

➡ 2n free parameters $(n_k, m_k)$

**$W_{tree}$ does not depend on T because of axion shift symmetry + holomorphicity**

# Tree-level moduli stabilisation (GKP)

- **Tree-level scalar potential:**

$$V_{tree} = e^K \left[ K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3|W|^2 \right] \qquad D_I W = W_I + W K_I$$

$$= e^K \sum_{S,U} K^{\alpha\bar{\beta}} D_\alpha W D_{\bar{\beta}} \overline{W} + e^K \left[ \sum_T K^{i\bar{j}} D_i W D_{\bar{j}} \overline{W} - 3|W|^2 \right]$$

$$= e^K \sum_{S,U} K^{\alpha\bar{\beta}} D_\alpha W D_{\bar{\beta}} \overline{W} + e^K \underbrace{\left[ \sum_T K^{i\bar{j}} K_i K_{\bar{j}} - 3 \right]}_{=0} |W|^2 \geq 0$$

No-scale cancellation !

- **Fix S and U supersymmetrically:**

$$\boxed{D_S W = 0} \qquad \boxed{D_{U_\alpha} W = 0} \quad \Rightarrow \quad W_0 \equiv < W_{tree} >$$

n real non-linear eqs. in n unknowns with 2n parameters ➡ enough freedom to find solutions

- **Number of solutions:** if each flux quanta can take 10 different values (D3 tadpole cancell.)

$$N_{sol} \approx 10^{2n} = 10^{4(h^{1,2}+1)} \approx 10^{400} \qquad \text{for } h^{1,2} \approx O(100)$$

Flux landscape

- **Minkowski vacuum with SUSY breaking** since $F^T \neq 0$ but T-moduli are flat!

$$m_{3/2} = e^{K/2}|W| \approx \frac{W_0}{\mathcal{V}} M_P$$

Naturally $W_0 \sim O(1)$ but can tune $W_0 << 1$

# Perturbative vs Non perturbative

- **In general:**

$$\mathcal{K} = \mathcal{K}_0 + \mathcal{K}_p + \mathcal{K}_{np} \approx \mathcal{K}_0 + J,$$
$$W = W_0 + W_{np} \approx W_0 + \Omega,$$

$$V = V_0 + V_J + V_\Omega + \cdots,$$

- **Then:**

$$V_0 \sim W_0^2, \quad V_J \sim J W_0^2, \quad V_\Omega \sim \Omega^2 + W_0 \Omega,$$

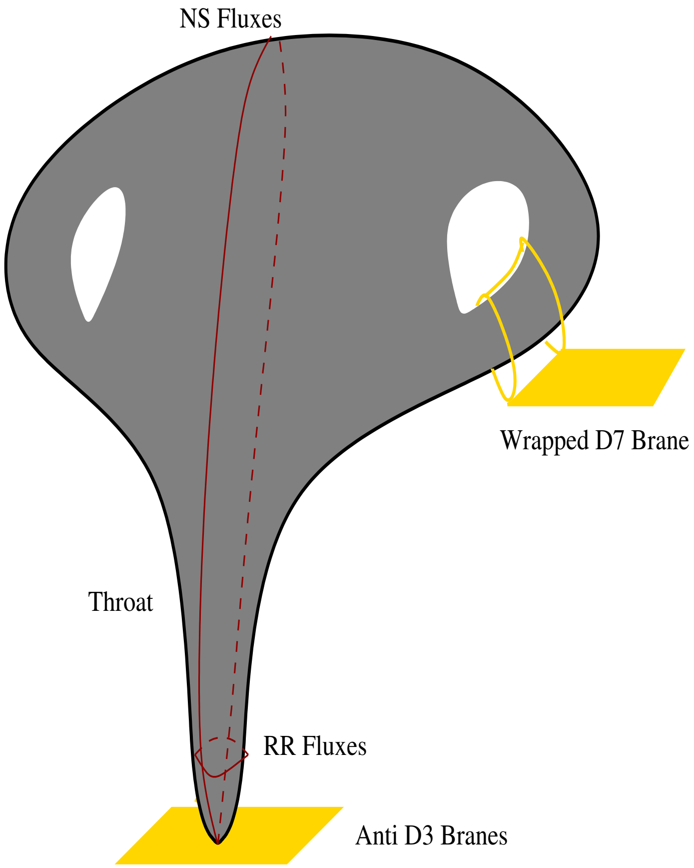
- **Usually $V_0$ dominates but $V_0$=0 no-scale**

$$G^{-1}_{i\bar{k}} \mathcal{K}_i \mathcal{K}_{\bar{k}} = 3$$

- **Dominant term is $V_J$** (e.g. LVS)

- **Unless $W_0$<<1** (e.g. KKLT)

# KKLT Scenario




**Warning: The control status of these approaches is under heated debate !**

# KKLT

- **Nonperturbative effects:** $$W_{np} = \sum A_i e^{-a_i T_i}$$

**SUSY AdS Vacua: DW=0**

- **Anti D3 brane (SUSY breaking+uplift)**

$$V_{\rm uplift} = \frac{D^2}{(T+T^*)^\alpha} = \frac{D^2}{\mathcal{V}^{2\alpha/3}} \qquad \begin{cases} \alpha = 3 & \text{KKLT} \\ \alpha = 2 & \text{KKLMMT} \end{cases}$$

**Can be supersymmetrised in EFT by a goldstino nilpotent superfield X, $X^2=0$ !**

# Large Volume Scenario (LVS)

- **Flux superpotential** $W_0$ (U,S)
- **Perturbative corrections to K** $K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right)$
- **Nonperturbative contributions to W**: $W_{np} = \sum A_i e^{-a_i T_i}$

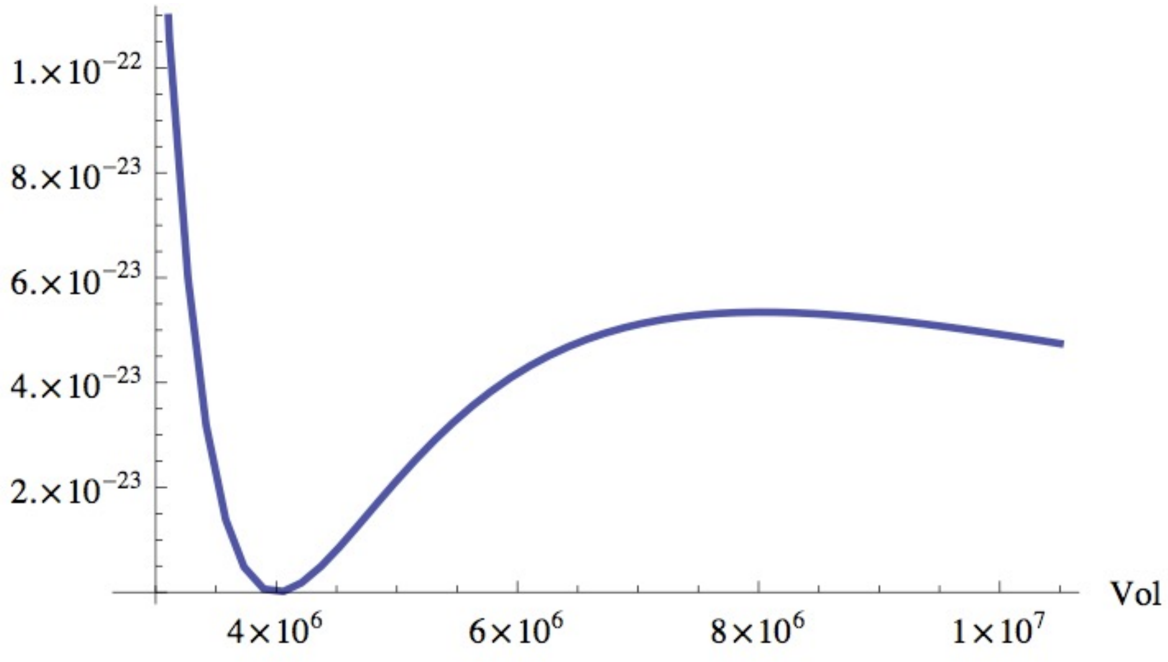
$$V_F \propto \left(\frac{K^{S\bar{S}}|D_S W|^2 + K^{a\bar{b}} D_a W \bar{D}_{\bar{b}} \bar{W}}{\mathcal{V}^2}\right) + \left(\frac{Ae^{-2a\tau}}{\mathcal{V}} - \frac{Be^{-a\tau}W_0}{\mathcal{V}^2} + \frac{C|W_0|^2}{\mathcal{V}^3}\right)$$

$$\boxed{\mathcal{V} \sim e^{a\tau}} \quad \text{with} \quad \tau \sim \text{Re S} \sim 1/\text{g}_\text{s} > 1.$$

**Exponentially large volume for weak coupling !**

# dS Kahler Moduli Stabilisation

$$V_F^{\rm tot} = V_{\rm np} + V_{\alpha'} + V_{\rm uplift}$$



# Relevant Scales

- String scale $Ms = M_P / V^{1/2}$
- Kaluza-Klein scale $M_{KK} = M_P / V^{2/3}$
- Gravitino mass $m_{3/2} = W_0 \, M_P / V$
- Volume modulus mass $M_V = M_p / V^{3/2}$
- Lighter (fibre) moduli $M_l = M_p / V^{5/3}$

# e.g. SUSY Breaking

| | **KKLT** | **LVS** |
|---|---|---|
| Soft term | D3 | D3 |
| $M_{1/2}$ | $\pm\left(\frac{3}{2a\mathcal{V}^{2/3}}\right)\, m_{3/2}$ | $\pm\left(\frac{3s^{3/2}\xi}{4\mathcal{V}}\right)\, m_{3/2}$ |
| $m_0^2$ | $\left(\frac{s^{3/2}\xi}{4\mathcal{V}}\right) m_{3/2}^2$ | $\left(\frac{5s^{3/2}\xi}{8\mathcal{V}}\right)\, m_{3/2}^2$ |
| $A_{ijk}$ | $-(1 - s\partial_s \log Y_{ijk})\, M_{1/2}$ | $-(1 - s\partial_s \log Y_{ijk})\, M_{1/2}$ |

| | **KKLT** | **LVS** |
|---|---|---|
| Soft term | D7 | D7 |
| $M_{1/2}$ | $\pm\left(\frac{1}{a\mathcal{V}^{2/3}}\right) m_{3/2}$ | $\pm\left(\frac{3}{4a\tau_s}\right) m_{3/2}$ |
| $m_0^2$ | $(1 - 3\omega)\, m_{3/2}^2$ | $\left(\frac{9(1-\lambda)}{16a^2\tau_s^2}\right)\, m_{3/2}^2$ |
| $A_{ijk}$ | $\frac{3}{2}(2\lambda - 1 - s\partial_s \log Y_{ijk})\, M_{1/2}$ | $-3(1 - \lambda)\, M_{1/2}$ |

# e.g. SUSY Breaking

- Split Supersymmetry $m_0 \sim 50\ M_{1/2}$

  $m_0 \sim 1000\ M_{1/2}$

  $M_{1/2} \sim 1$ TeV

**(Concrete realisation of split susy in a framework including landscape, relative scales fixed, matching well with experiments...)**

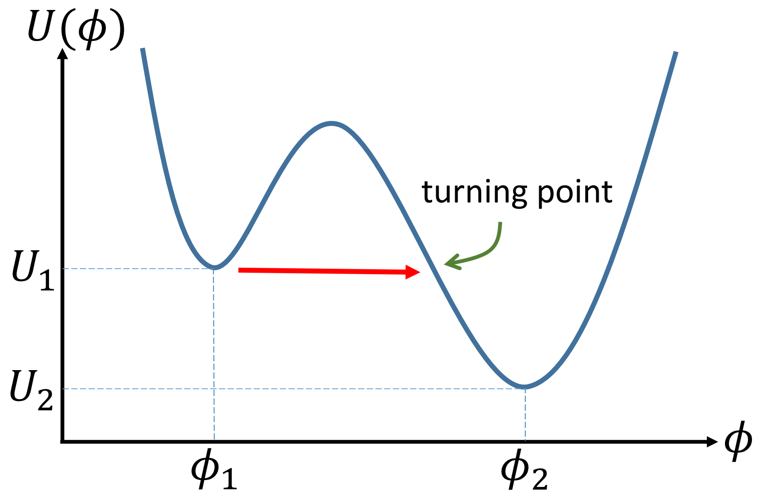
- High energy SUSY $m_0 \sim M_{1/2} \sim 10^{11}$ GeV

# Axions

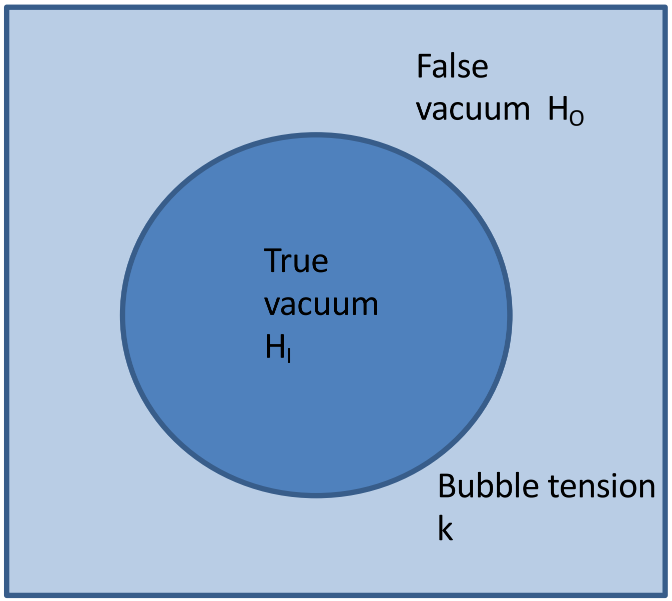
- Model independent axion partner of volume,
  mass≈exp(-$V^{2/3}$) ≤ $10^{-22}$ eV
  (dark energy, matter, radiation).
- Some massive by Stuckelberg effect
- Others massive from non-perturbative effects
- Open string axions (model dependent)

# String Landscape

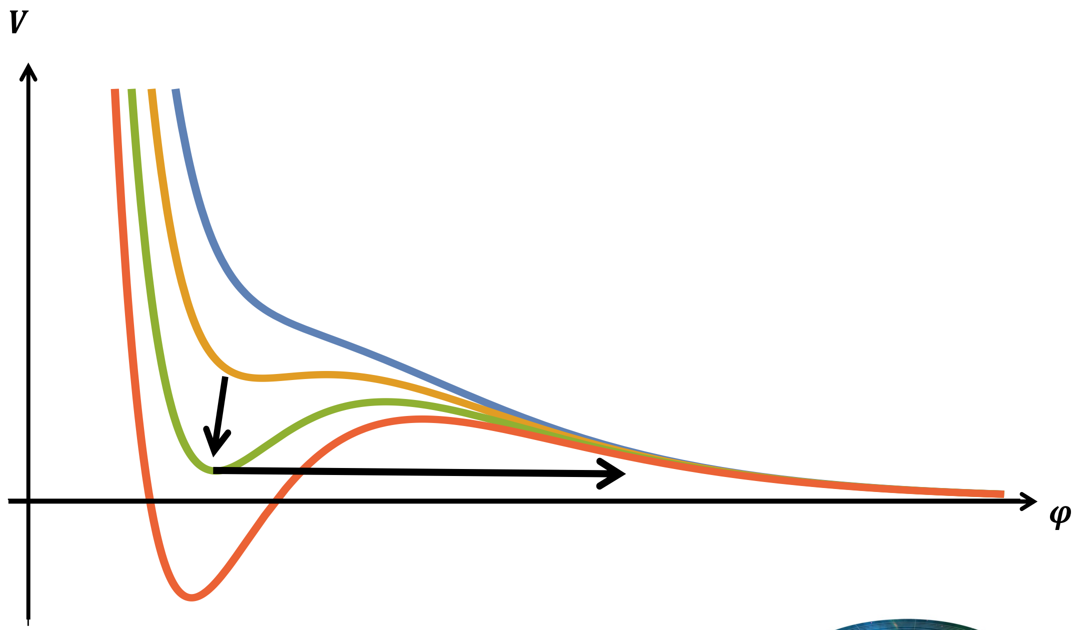
# Vacuum transitions

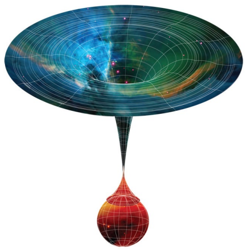



**Bubble nucleation**



# Transitions in the landscape



1. **Flux transitions** (induced by D5/NS5 nucleation)

Brown-Teitelboim 87

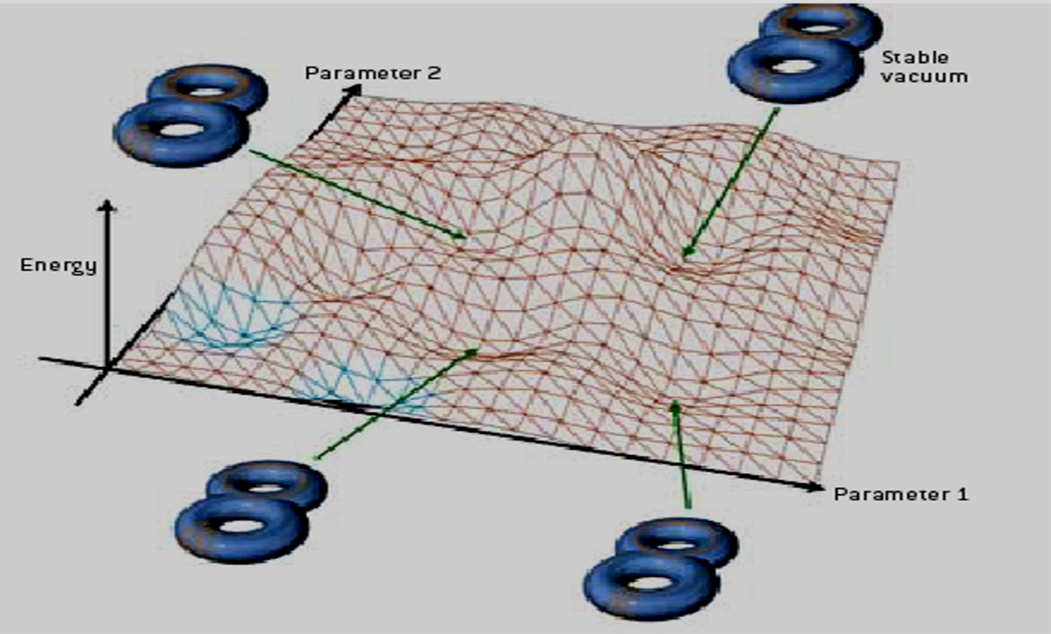
2. **Decompactification**

Coleman-De Luccia 1980

$$\Gamma_{\text{flux}} \ll \Gamma_{\text{decompactification}} \qquad e.g. \qquad \Gamma_{\text{flux}} \sim e^{-\mathcal{V}^2}\Gamma_{\text{decompactification}}$$

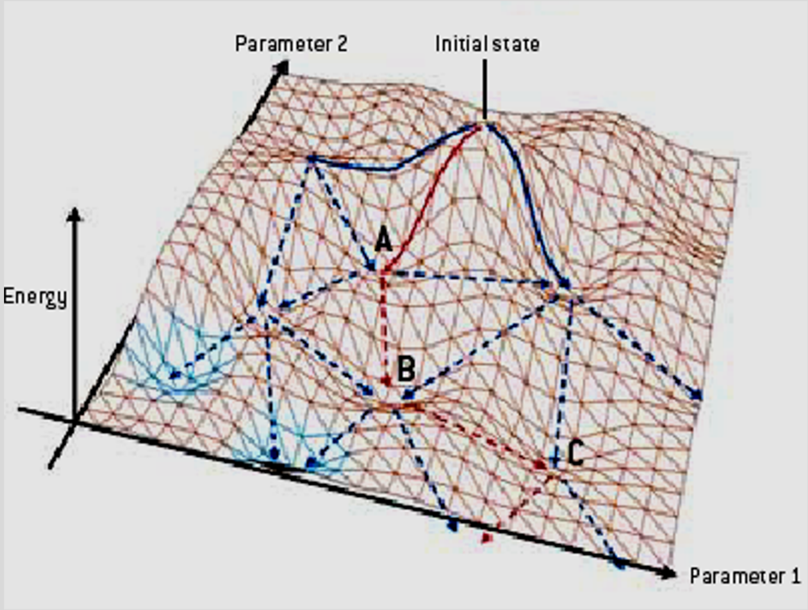
**(In LVS)**

# The String Landscape




Classical Solutions

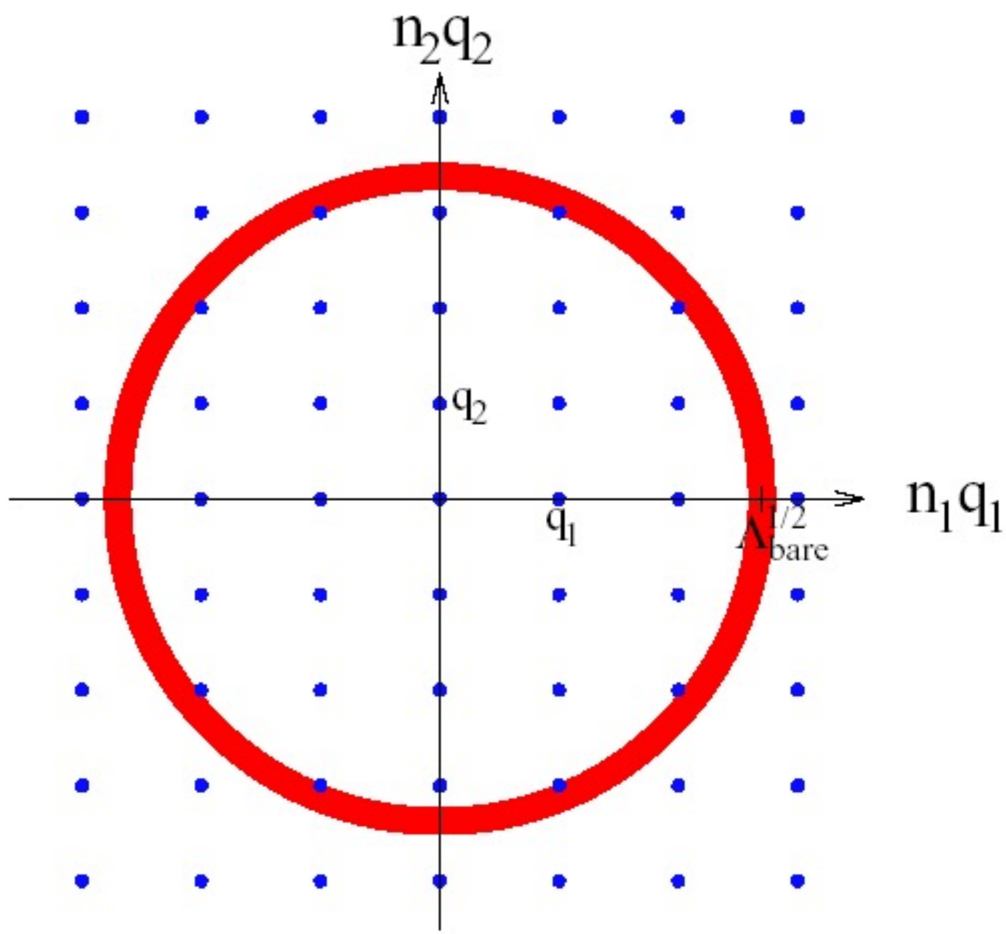
Quantum Decay
(tunnel effect)




Warning: just a cartoon!

Bousso+Polchinski

# Cosmological Constant (?)




Bousso-Polchinski 2000,
Weinberg 1987

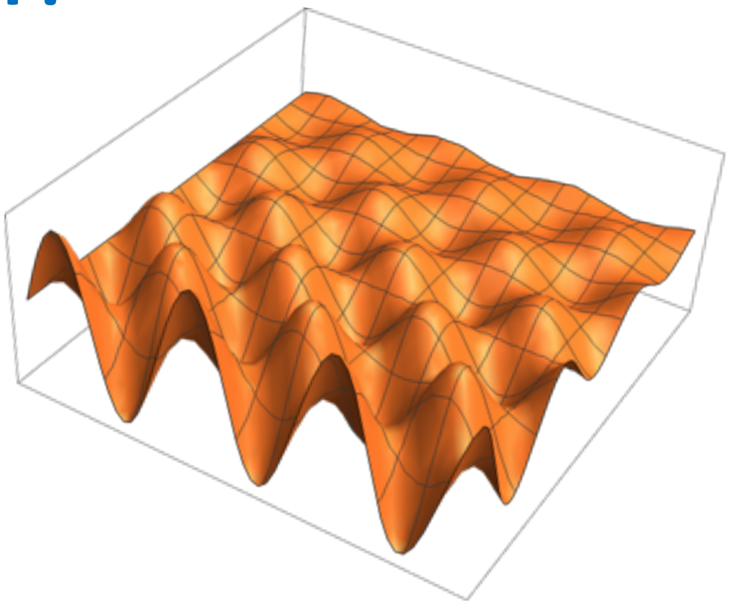
# The String Landscape and Dark Energy

- **Anthropic prediction $\Lambda \sim 10^{-120}$** (Weinberg 1987)
- **Concrete proposal** (Bousso-Polchinski 2000)
- **Explicit String realization** (KKLT, LVS,… 2003)

**The worst solution to the dark energy problem with the exception of all the others!**
(smallness of $\Lambda$ not a good question)

# Predictions from the landscape?

- Bubble nucleations imply open universe!?
- Not possible to tunnel up from Minkowski nor anti de Sitter?



# The Landscape

- **Good:** A `solution' of dark energy and allows  for the first time to trust calculations for low-energy SUSY breaking.

- **Bad:**  missed opportunity to have new physics at low energies from small $\Lambda$.

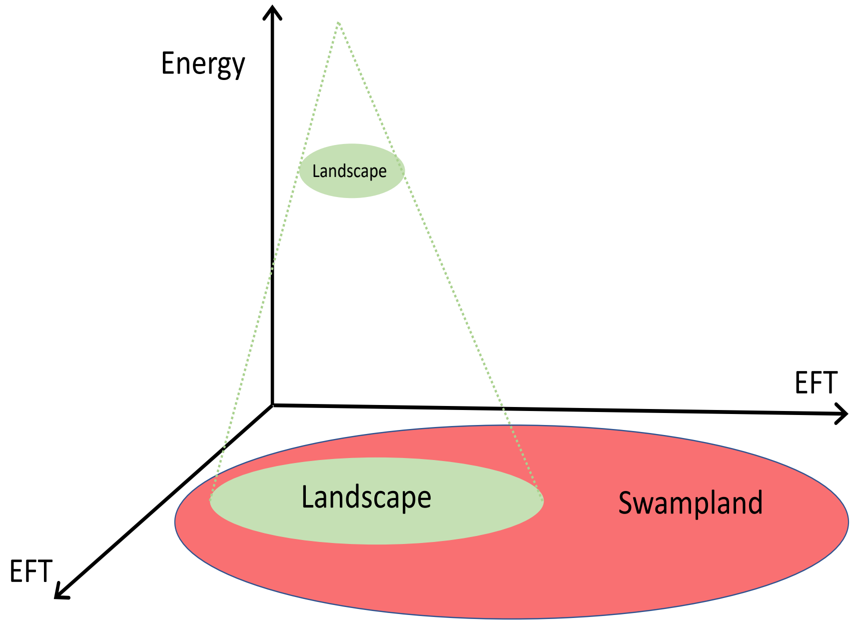
- **Ugly:** It may also be used to `solve' other problems  (Split SUSY, High-energy SUSY,…) in unnatural ways.

# NOT yet a solution to dark energy

- Not yet concrete models with so many fluxes (so far only a handful of moduli, need 100s or thousands)
- Need to populate the landscape
- Distribution of fluxes (measure problem, etc.)

# The Swampland

# The Swampland

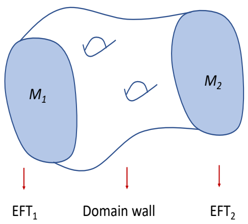


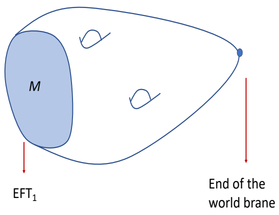

**Set of consistent low-energy EFTs without UV completion**

# Swampland conjectures

Vafa et al.

- **Swampland: Quantum gravity vs EFT !**
- **Weak gravity conjecture**
- **No global symmetries**
- **Cobordism conjecture**
- **Distance conjecture**




- **'anti'- de Sitter conjecture:**

(It would imply quintessence and no de Sitter and hard to have inflation!).?

$$M_p \frac{|\nabla V|}{V} \gtrsim c \,,$$

- **TransPlanckian Conjecture, emergence conjecture,…**

**So far, the more rigorous the less relevant phenomenologically.**

# String Cosmology

# Before inflation?

# Wave functions of the universe

## Mini-superspace

$$ds^2 = -N^2(t)dt^2 + a^2(t)(dr^2 + \sin^2 r d\Omega_2^2)$$

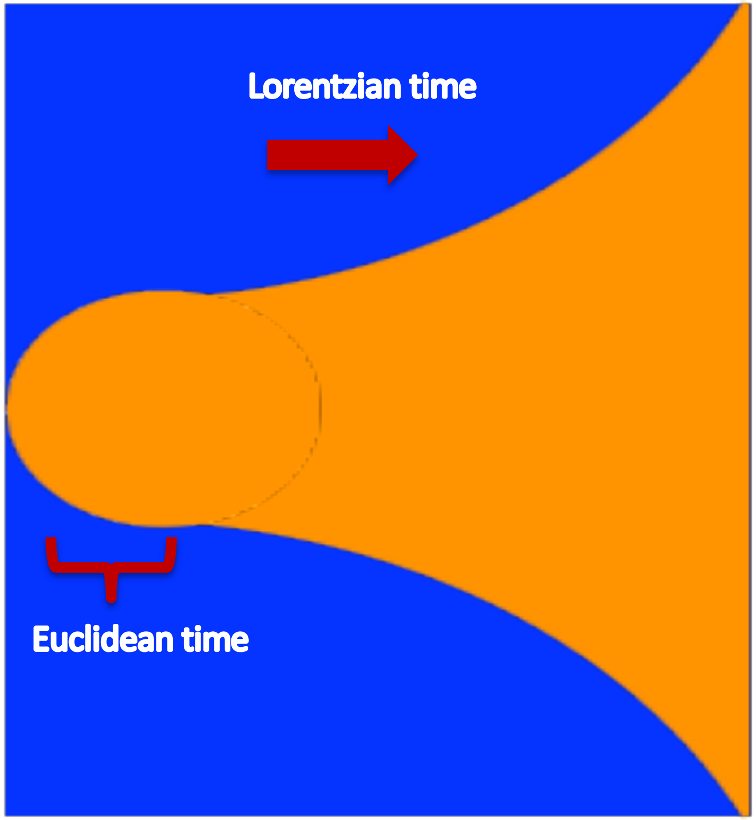
## Hartle-Hawking vs Vilenkin (tunneling to dS from nothing)

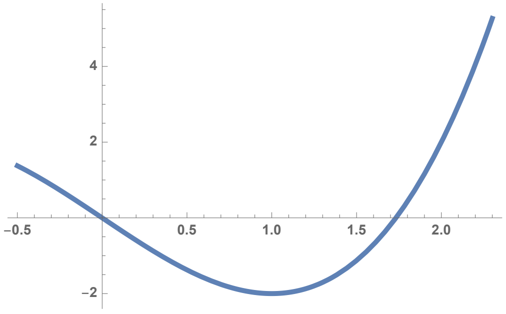
entropy

$$\mathcal{P}_{\mathrm{HH}}(\mathrm{Nothing} \to \mathrm{dS}) = \|\Psi_{\mathrm{HH}}(\mathrm{H_{dS}})\|^2 \propto e^{\frac{\pi}{GH_{\mathrm{dS}}^2}} = e^{+S_{\mathrm{dS}}}$$

$$\mathcal{P}_{\mathrm{T}}(\mathrm{Nothing} \to \mathrm{dS}) = \|\Psi_{\mathrm{T}}(\mathrm{H_{dS}})\|^2 \propto \mathrm{e}^{-\frac{\pi}{\mathrm{GH_{dS}^2}}} = e^{-S_{\mathrm{dS}}}$$

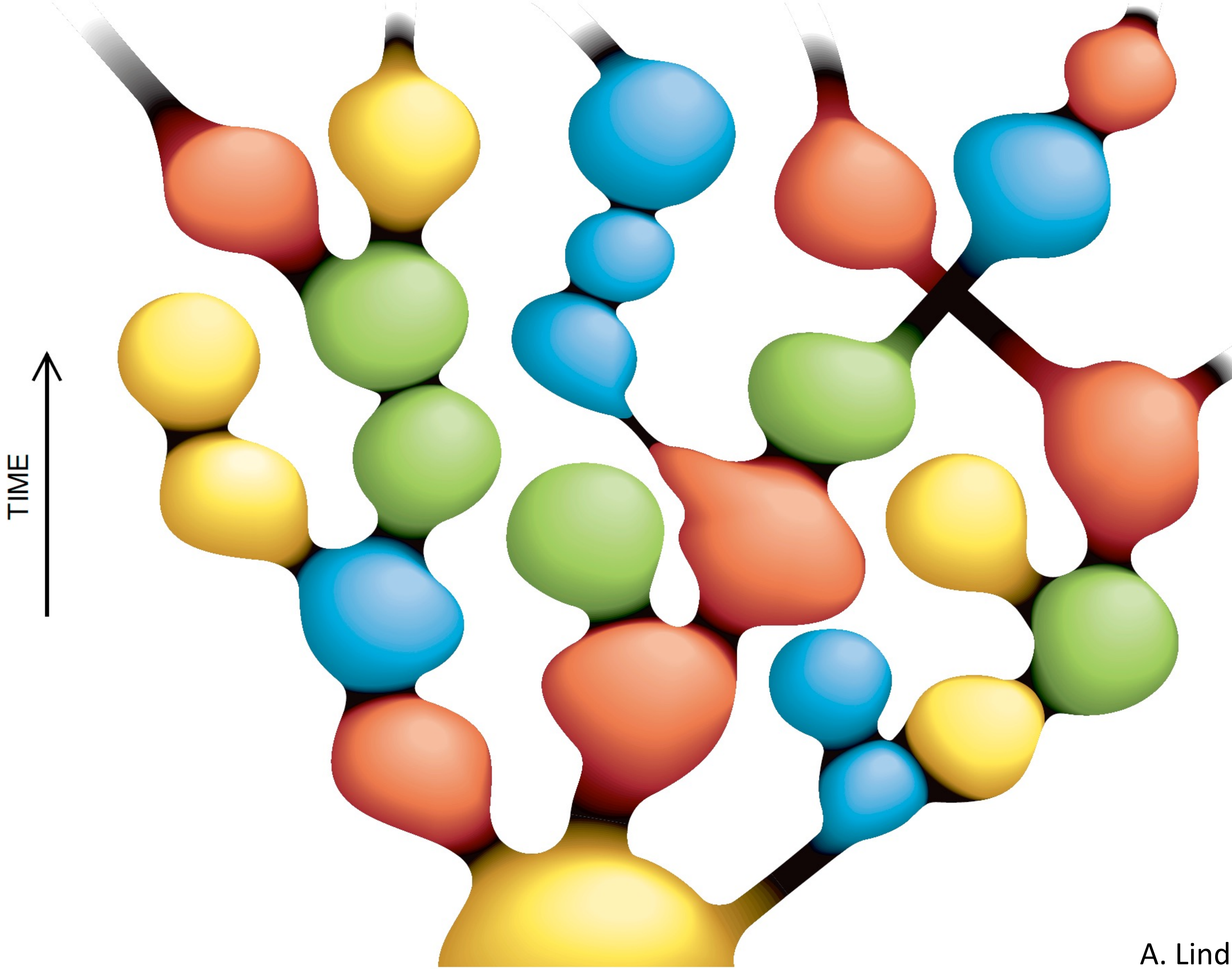
# Transition from nothing?



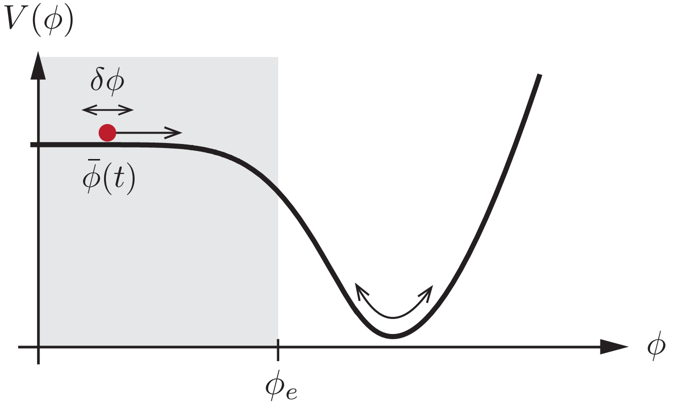

$$\mathcal{H} = -\frac{\pi_a^2}{12a} - 3a + a^3\Lambda$$

Wheeler-DeWitt, Vilenkin, Hartle-Hawking



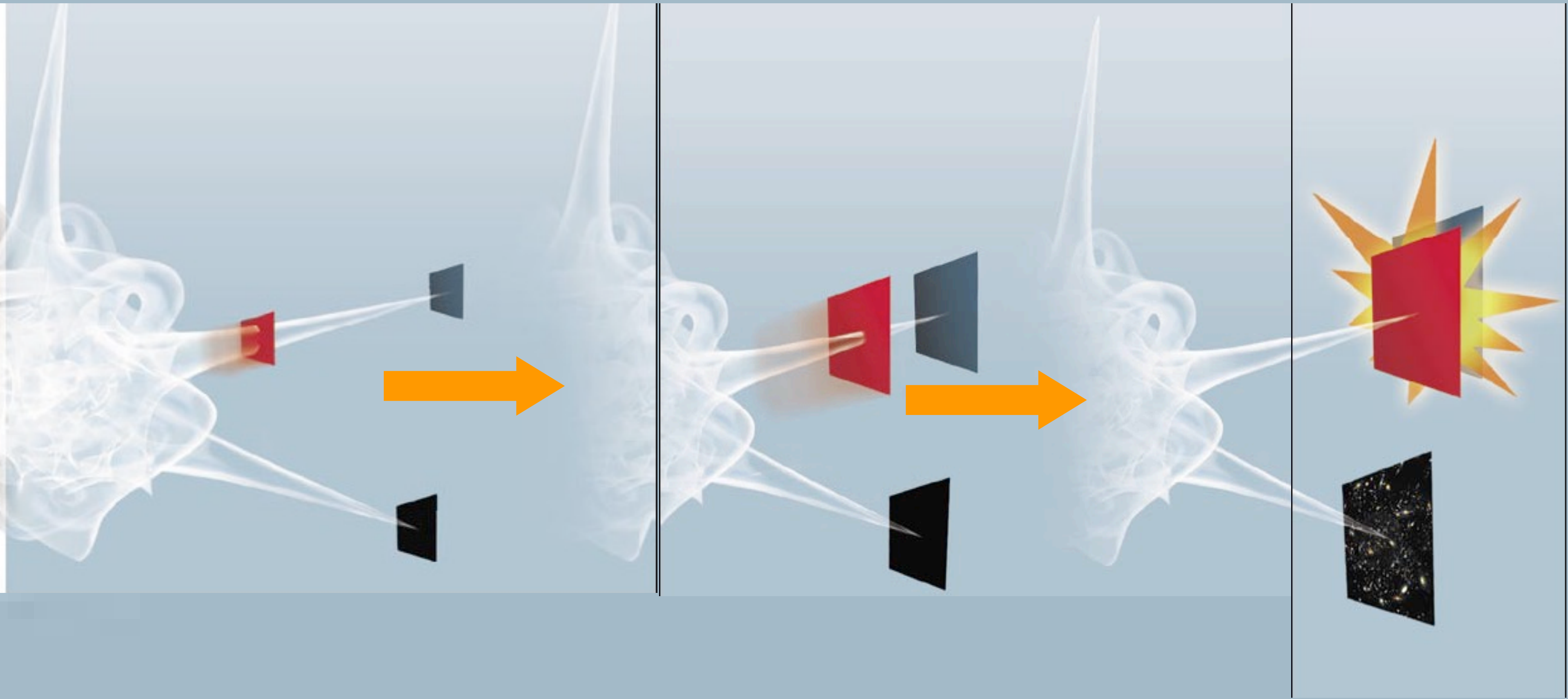

A. Linde

# String Inflation

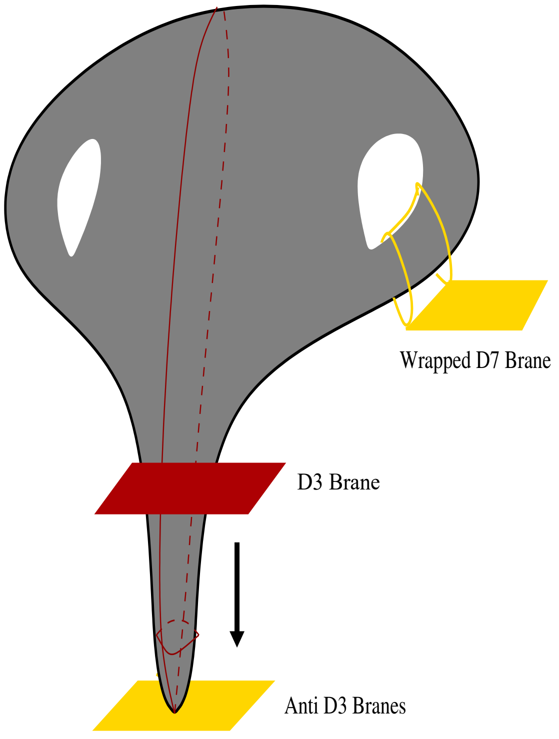


e.g.

# Brane/antibrane inflation

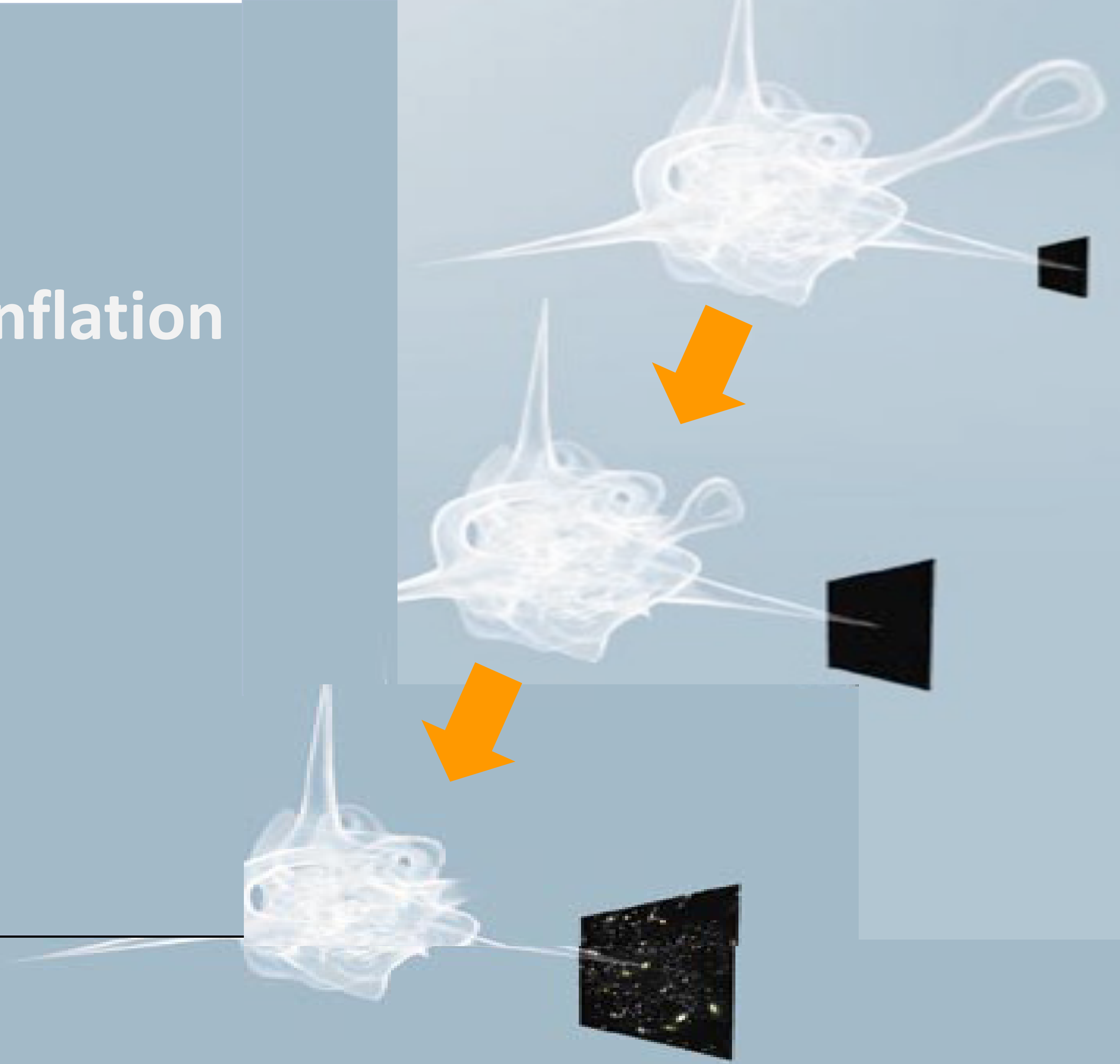


# e.g. Brane/Antibrane Inflation



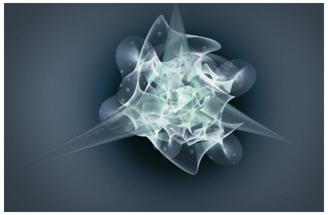
e.g.

# Moduli inflation



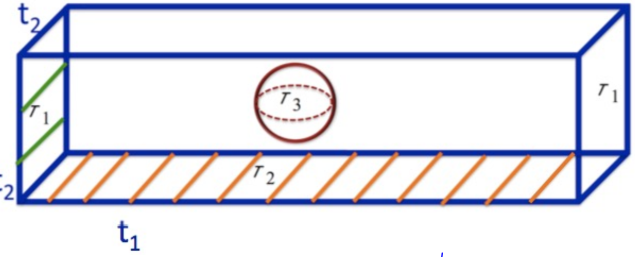
# e.g. Kahler moduli

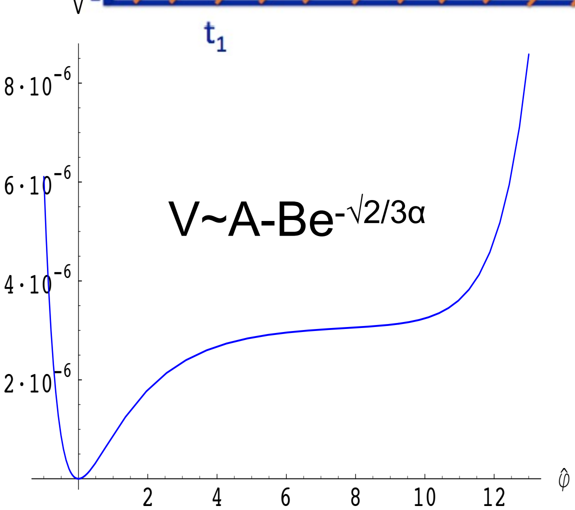
- **Overall volume**



- **Blow-up**

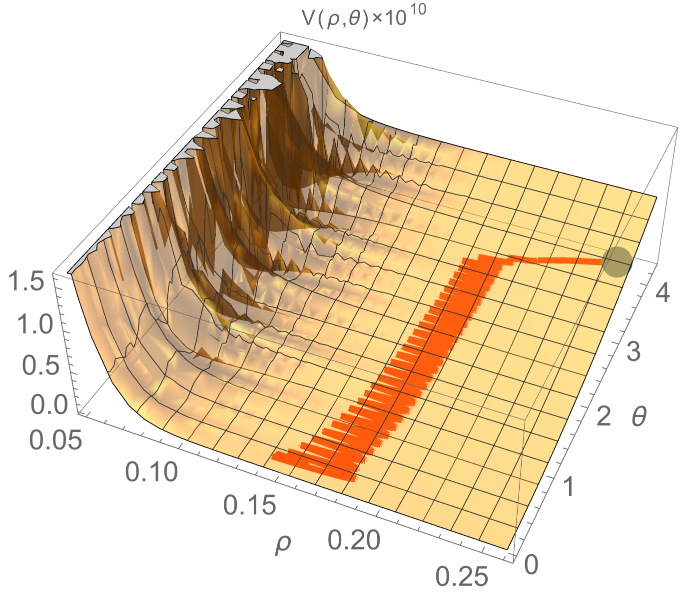
- **Fibre moduli**



# e.g. Axion Monodromy

$$V = \frac{M^2}{\beta}\left(\rho^2 + \theta^2 + \frac{2\lambda}{M}\, e^{-b\rho}\left[\theta\,\cos\left(b\,\theta\right) + \rho\,\sin\left(b\,\theta\right) + \frac{\lambda}{2M}\, e^{-b\rho}\right]\right),$$

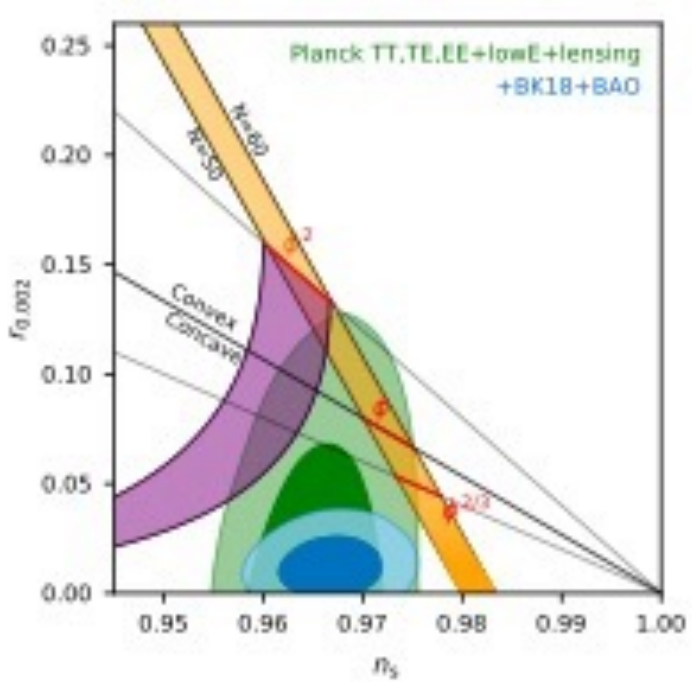


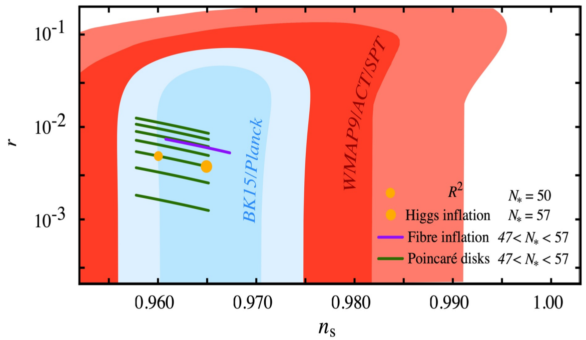
# Predictions of String Inflation Models

| **String model** | $n_s$ | $r$ |
|---|---|---|
| Fibre Inflation | 0.967 | 0.007 |
| Blow-up Inflation | 0.961 | $10^{-10}$ |
| Poly-instanton Inflation | 0.958 | $10^{-5}$ |
| Aligned Natural Inflation | 0.960 | 0.098 |
| $N$-Flation | 0.960 | 0.13 |
| Axion Monodromy | 0.971 | 0.083 |
| D7 Fluxbrane Inflation | 0.981 | $5 \times 10^{-6}$ |
| Wilson line Inflation | 0.971 | $10^{-8}$ |
| D3-$\overline{\text{D3}}$ Inflation | 0.968 | $10^{-7}$ |
| Inflection Point Inflation | 0.923 | $10^{-6}$ |
| D3-D7 Inflation | 0.981 | $10^{-6}$ |
| Racetrack Inflation | 0.942 | $10^{-8}$ |
| Volume Inflation | 0.965 | $10^{-9}$ |
| DBI Inflation | 0.923 | $10^{-7}$ |

# Recent BICEP/KECK 2021 results

$$r_{0.05} = 0.014^{+0.010}_{-0.011} \; (r_{0.05} < 0.036 \text{ at } 95\% \text{ confidence})$$

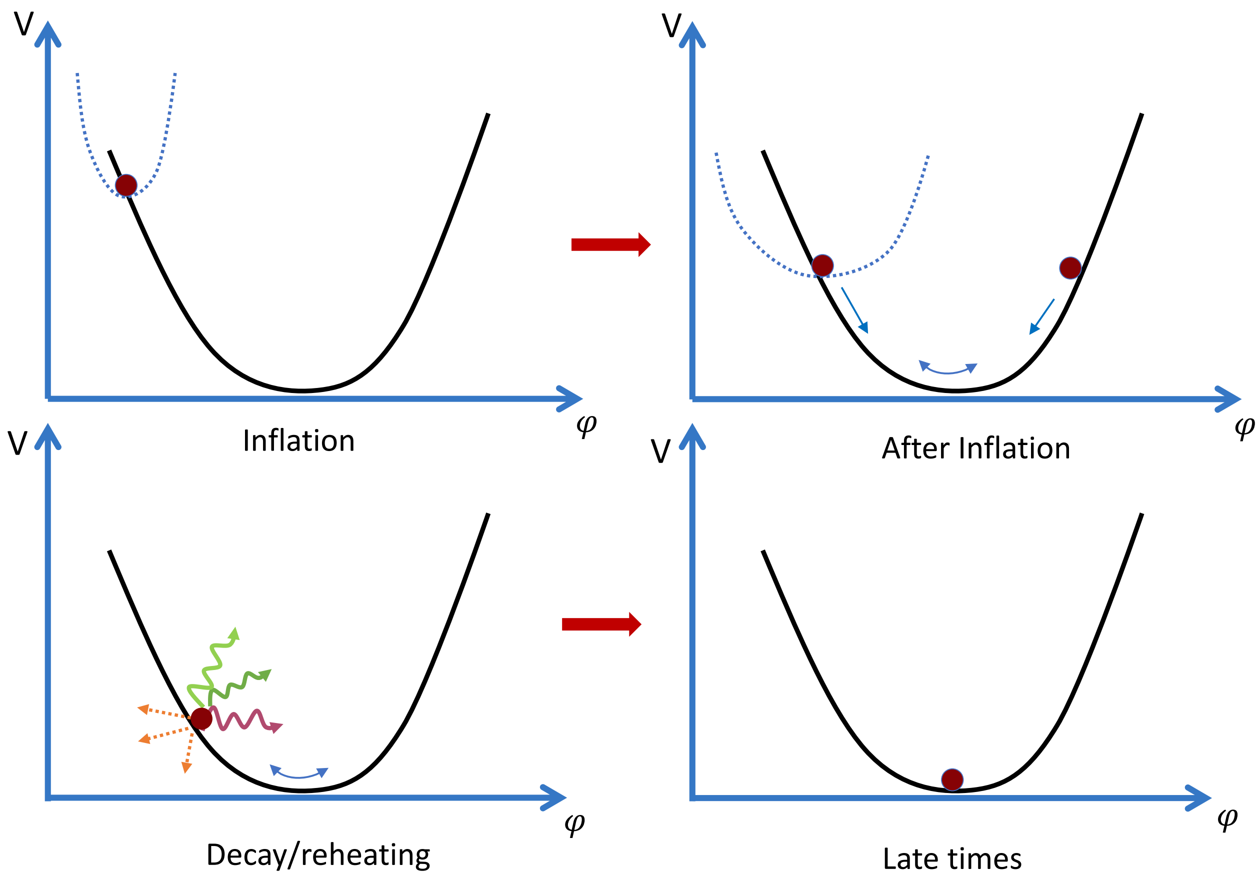



From Flauger 2021 (see Kallosh-Linde)

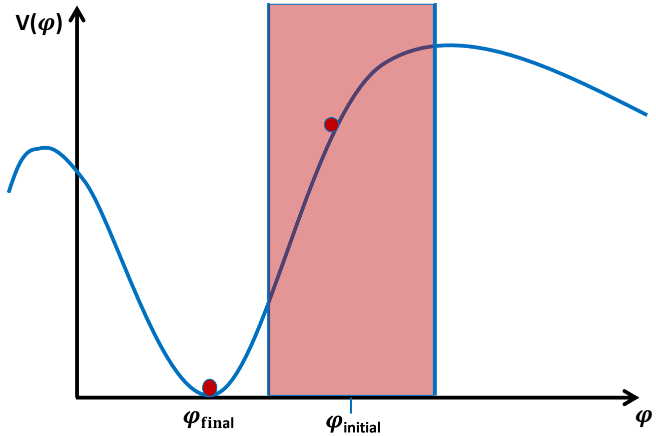
# After Inflation

# Moduli Domination

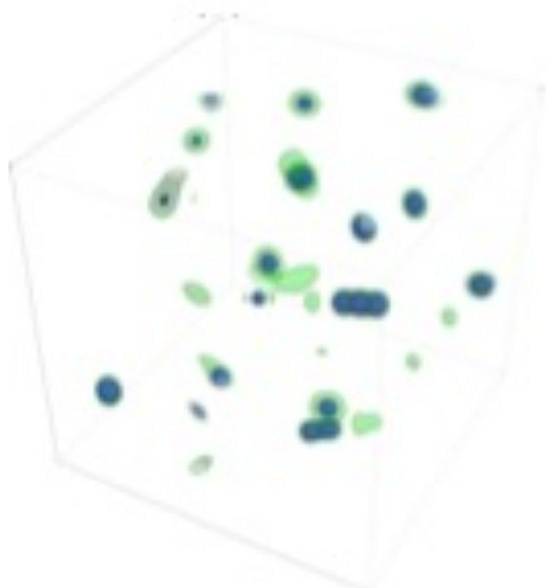


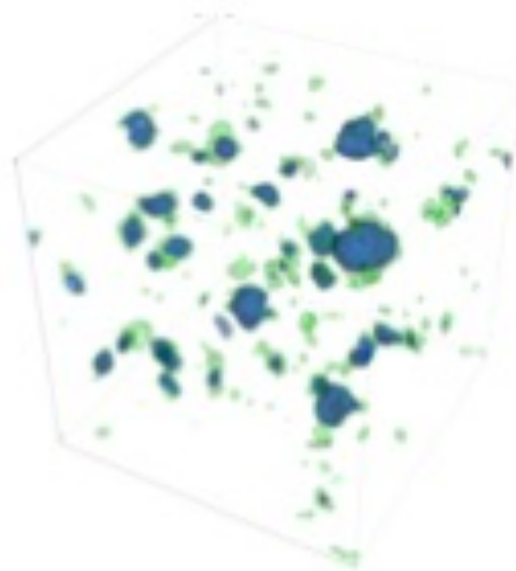

**Reheating from latest moduli to decay NOT from inflaton!**

# Oscillons/Moduli stars?



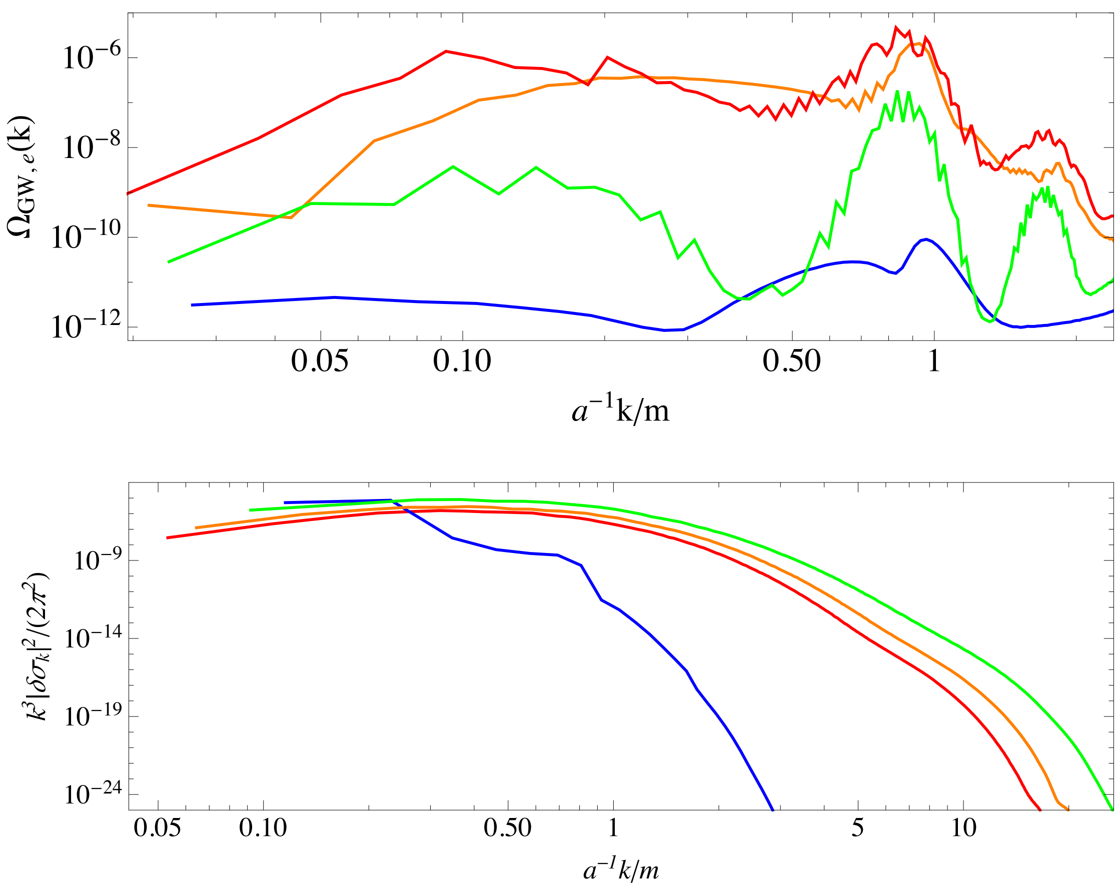

KKLT



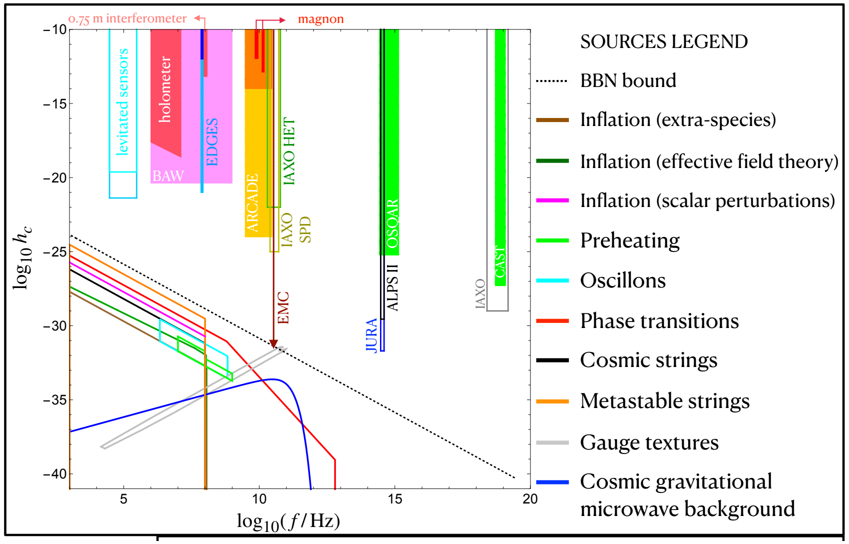


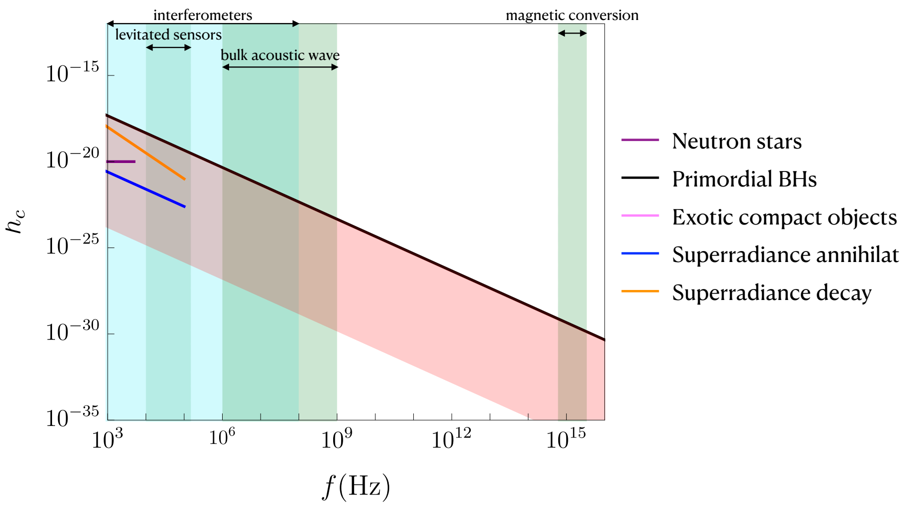
LVS

# Gravitational Waves Spectrum

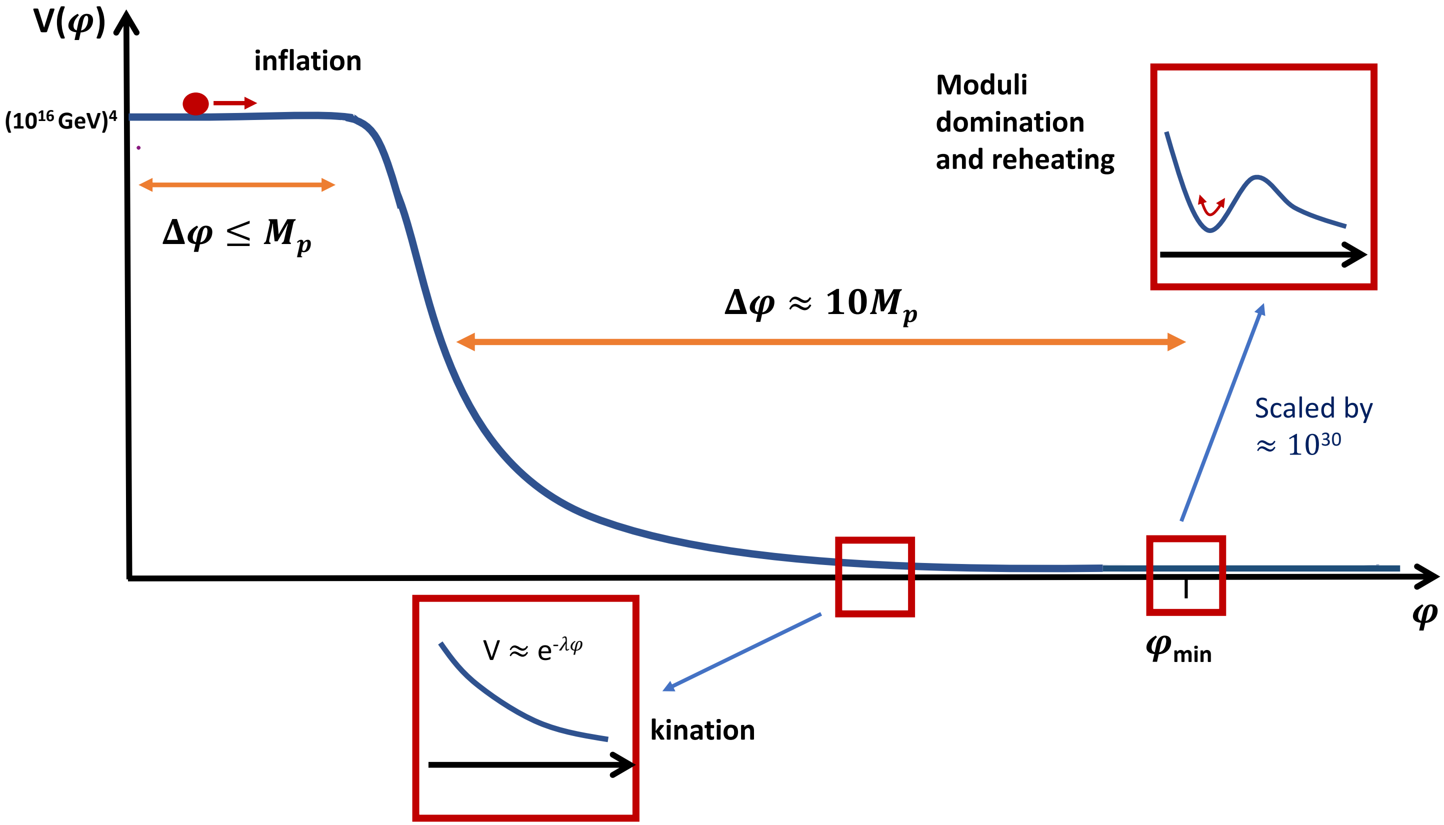


# Gravitational Waves High Frequency



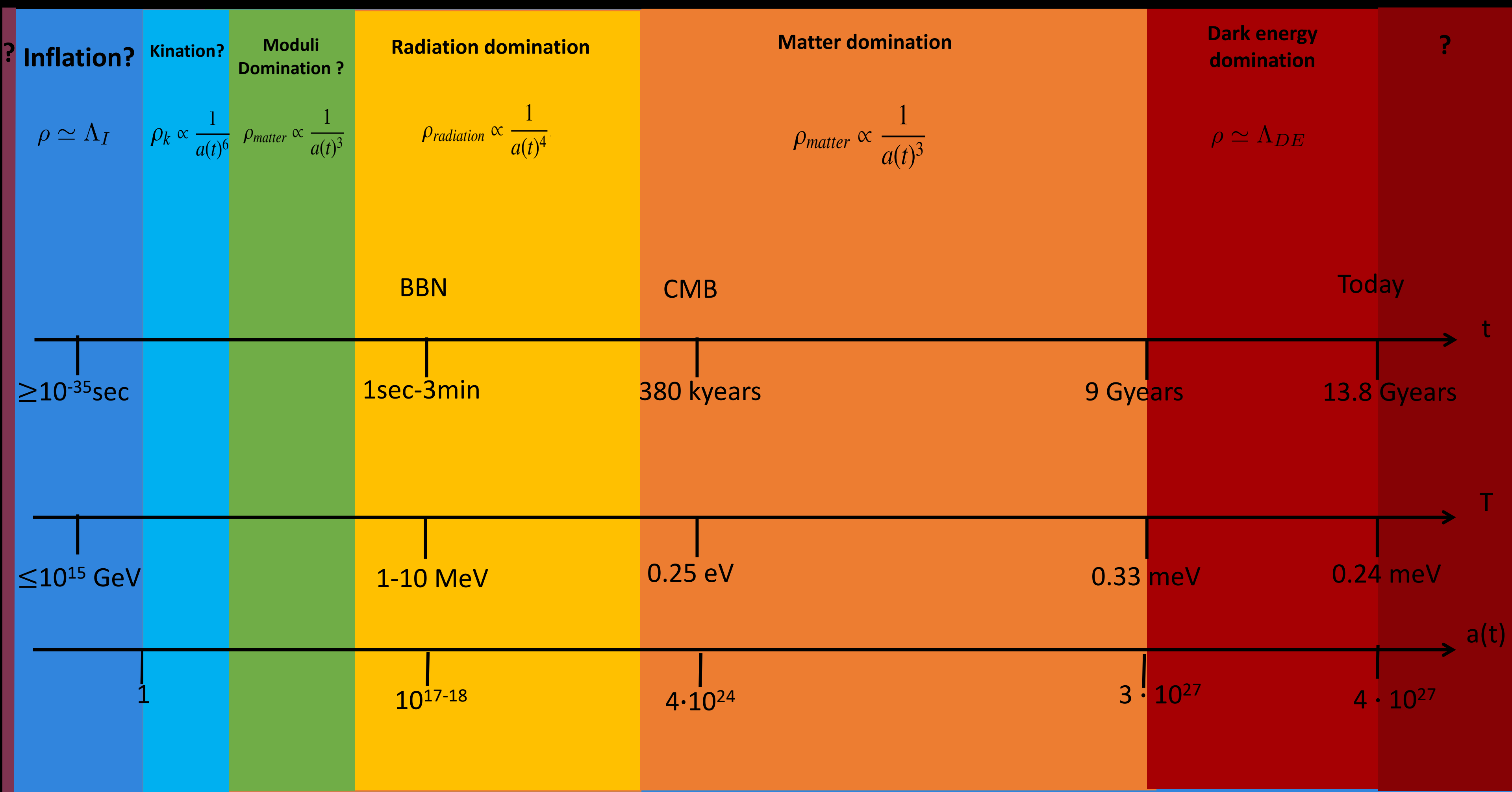



# Kination scenario



# Alternative Histories?

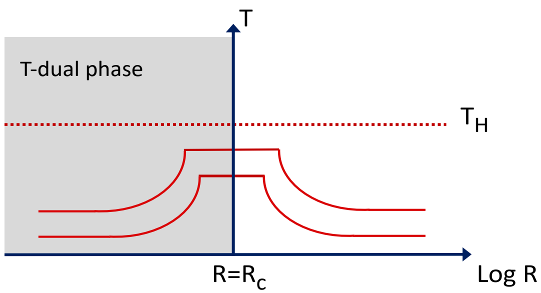
**Alternative histories of our Universe**



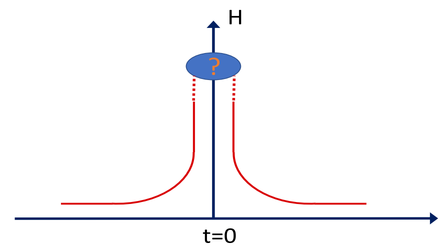
# Alternatives to String Inflation

# Alternatives to String Inflation

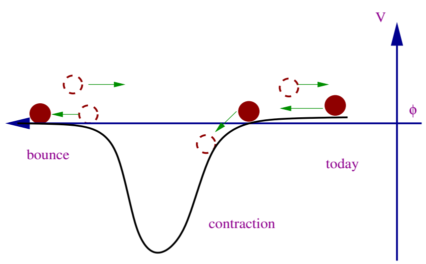
**String gas**



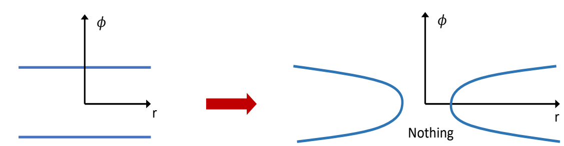

**Pre big-bang**



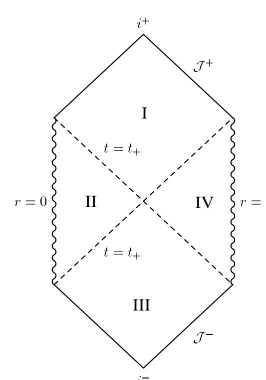

**Ekpyrotic /cyclic**




**Bubble of nothing**




**S-branes/ Rolling tachyons**



# Thank You!